NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

DEFENSIVE MINEFIELD PLANNING

by

Carlos Vallejo Game

June 1989

Thesis Advisor: Alan Washburn

Approved for public release; distribution is unlimited

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION: Unclassified	1b RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: Naval Postgraduate School; 6b. OFFICE SYMBOL (If applicable): 55	7a. NAME OF MONITORING ORGANIZATION: Naval Postgraduate School
6c. ADDRESS (City, State, and ZIP Code): Monterey, California 93943-5000	7b ADDRESS (City, State, and ZIP Code): Monterey, California 93943-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION; 8b. OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10 SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO; PROJECT NO; TASK NO; WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
Defensive Minefield Planning

12. PERSONAL AUTHOR(S)
LT Carlos Vallejo Game

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Master's thesis	FROM ____ TO ____	June 1989	86

16. SUPPLEMENTARY NOTATION The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Defensive Minefield, Mine deployment, Mine countermeasure, Shock Factor

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This thesis is concerned with the problem of constructing an optimal minefield for inflicting casualties to a naval force attempting to penetrate the field. A microcomputer based simulation program dealing with this problem is presented and permits the user to select various mine characteristics (charge weight, depth, sensitivity), number of mines, number of transitting ships and navigational error.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL: Alan Washburn	22b TELEPHONE (Include Area Code): 408-646-3127; 22c OFFICE SYMBOL: 55Ws

DD Form 1473, JUN 86 Previous editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

S/N 0102-LF-014-6603

Defensive Minefield Planning

by

Carlos Vallejo Game
Lieutenant, Ecuadorian Navy
B. S., Escuela Superior Naval, Ecuador 1980

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
June 1989

ABSTRACT

This thesis is concerned with the problem of constructing an optimal minefield for inflicting casualties to a naval force attempting to penetrate the field. A microcomputer based simulation program dealing with this problem is presented and permits the user to select various mine characteristics (charge weight, depth, sensitivity), number of mines, number of transitting ships and navigational error.

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

TABLE OF CONTENTS

I. INTRODUCTION 1

A. STATEMENT OF THE PROBLEM 1

B. IMPORTANCE OF NAVAL MINE WARFARE 2

C. OBJECTIVE..3

D. SCOPE..3

II. HISTORY OF MINES AND THE INTERNATIONAL LAW...........5

A. MINES DEVELOPMENTS BETWEEN USA CIVIL WAR AND WWI..5

B. USES OF MINES DURING AND AFTER WORLD WAR I........6

C. USES OF MINES DURING AND AFTER WORLD WAR II.......8

D. THE MINE IN INTERNATIONAL LAW.....................11

III. CHARACTERISTICS AND TYPES OF MINES AND MINEFIELDS...14

A. TYPES OF MINES....................................14

B. TYPES OF MINEFIELDS...............................20

C. MINE DEPLOYMENT...................................23

D. MINE COUNTERMEASURES..............................24

IV. UNDERWATER EXPLOSIONS.................................27

A. UNDERWATER EXPLOSION PRINCIPLES...................27

B. THE SHOCK FACTOR..................................30

V. IMPLEMENTATION AND ANALYSIS OF A MINEFIELD MODEL....34

A. DESCRIPTION OF THE PROGRAM........................35

B. STRUCTURE OF THE PROGRAM..........................40

C. AN EXAMPLE..43

D. ASSUMPTIONS AND TEST CONDUCTED....................44

E. ANALYSIS OF THE RUNNING TIME.....................60

VI. SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDIES.....63

APPENDIX FORTRAN PROGRAM................................64

LIST OF REFERENCES......................................76

INITIAL DISTRIBUTION LIST...............................77

ACKNOWLEDGEMENTS

I wish to dedicate this thesis to my parents Reynaldo and Alicia and my sister Maria Isabel, for all their loving support during this course and to the Navy of Ecuador for making it possible for me to attend the Naval Postgraduate School.

I would like to thank my Thesis Advisor, professor Alan Washburn for his advice and technical guidance.

To my Second Reader, Professor Maurice Weir, I would like to express my gratitude for his editorial assistance.

Finally, I am especially grateful to my friend Lt Cdr. Newton Rodriguez Lima (Brazilian Navy) and his wife Marise Ferracciu for their brotherhood, friendship and moral support throughout this lengthy journey.

I. INTRODUCTION

A. STATEMENT OF THE PROBLEM

During a military conflict, sea ports of the involved nations become one of the main targets of the opposing naval forces, because those are the places where deployments of troops, equipments and supplies will be held. In addition, beaches are also under great threat, where disembarkation of amphibious troops and equipments can be deployed without delay, allowing enemy forces to infiltrate inside friendly lines.

In order to defend ports and beaches from a naval attack or to establish a blockade of enemy ports, it is attractive to lay down a minefield rather than to patrol the same area and expose one's own forces to enemy action.

During war, time is one of the most important factors. If troops, equipments, supplies or war vessels are urgently needed in another theater of war, their absence or difficulty in reaching it could be crucial. Delay may be just as important as attrition in the mind of the minefield planner. A minefield may achieve its objective without sinking any ships at all.

In peace time, mine warfare can only be studied. It cannot be practiced in the full sense of the term, as it is impossible for the economic, strategic, or political

effects to be simulated. This study will focus on the simulation of the traffic of ships through a minefield, given specific characteristics of the mines.

B. IMPORTANCE OF NAVAL MINE WARFARE

Naval Mine Warfare is a simple concept which is not fully appreciated. It is a relatively unknown subject for many individuals in decision making positions, even within the Navy, because they do not understand the characteristics or principles of Mine Warfare.

The main idea of Mine Warfare is to let the enemy run across the weapon, which lies in wait for its victim, rather than to let the weapon seek the enemy. The mine, once laid, is in constant readiness awaiting the opportunity to attack. It remains on station waiting and withholding its fire until its chance arrives. By employing mines one can achieve maximum effectiveness at minimum cost and risk to own forces.

Mine Warfare removes from consideration many of the conventional aspects of Warfare, e.g., face to face combat and the pursuit or capture of the enemy. Instead, Mine Warfare gives the enemy the option of not advancing, not moving his men and material by sea or risking severe losses by attempting to do so. In general, the philosophy on the use of mines has changed radically since the beginning of their use. In the early days mines were considered by some to be unethical; they were often referred to as devilish

devices. Today mines are considered legitimate naval weapons. This change of attitude has encouraged mine designers to improve the weapon and to build a great deal of sophistication into it. The modern mine is a smart weapon.

Mines can be expected to be used increasingly as their cost effectiveness is realized and as economic priorities limit the growth of military budgets. This is especially true in poorer countries of the world where military budgets do not permit the acquisition of increasingly expensive platforms and munitions.

C. OBJECTIVE

The objective of this thesis is to develop and evaluate a simulation-based tool for assessing the effectiveness of a minefield consisting of magnetic mines.

D. SCOPE

The contents of this thesis include:

Chapter I : A brief description of the problem and the importance of Naval Mine Warfare. Objective.

Chapter II : History of Mine Warfare development and its uses in different conflicts through time. Mine International law.

Chapter III:	General characteristics and types of mines and minefields, with emphasis on magnetic naval mines.
Chapter IV :	Effects of Under Water Explosions.
Chapter V :	Description of the simulation and a hypothetical example of its application.
Chapter VI :	Summary and recommendations for further studies.

II. HISTORY OF MINES AND THE INTERNATIONAL LAW

A. MINE DEVELOPMENTS BETWEEN UNITED STATES CIVIL WAR AND WORLD WAR I

Although the United States did very little research on mines between the Civil War and the beginning of World War I, other nations were very busy improving their mine capabilities.

In 1868, the Herz horn method of firing independent mines was invented by Dr. Herz, a member of the German Mine Defense Committee. This invention consisted of an electrolyte in a glass tube sheathed in a soft metal horn. When bent by contact with a ship, the glass would break and the electrolyte would complete the circuit in a battery which could then fire the electric detonator. This same year, moored and drifting mines were used in large quantities in the conflict that took place in South America between Brazil and Paraguay. In 1870, during the Franco-German war, the Jode, Elbe and Weser rivers were defended by minefields and thereafter the Germans took up the development of mining material with considerable vigour.

In 1898, in the Spanish-American war, a minefield with a small number of moored mines was planted around Santiago, Cuba against the shipping operation of the American fleet. There were no casualties [Ref. 1].

A major use of mines at sea in naval actions occurred during the Russo-Japanese war in 1904. Mines played a decisive role in this fight. The Japanese had realized the value of submarine mines and they equipped their navy with effective mines. At the very outset of the war, Russian naval strength in the East was seriously reduced as a result of attacks by the Japanese. The Russians, therefore, decided to mine the Russian ports in order to protect them. In all, Japan lost 2 battleships, 4 cruisers, 2 destroyers and 1 minelayer, while the Russians lost 1 battleship, 1 cruiser, 2 destroyers and a few small ships [Ref. 2] all to mines. This was the last conflict in which only military forces were the main aggressors as well as the main target. Subsequently, the sinking of commercial shipping was frequently a deliberate goal of the minefield planner.

B. USE OF MINES DURING AND AFTER WORLD WAR I

The Russo-Japanese war showed that mines were formidable weapons, and provided practical experiences and lessons for the other nations of the world. This war was followed by intense development of mining techniques by the Germans and British, with important assistance rendered by the United States. The naval mine emerged as the Allies' primary weapon against German submarines in World War I [Ref. 11].

Although the Germans laid several defensive minefields around their ports in order to keep out the British naval forces, their major use of mines was really offensive, laying mines in British estuaries and in their ports. The most important development of the Germans in their North Sea mine operations was the use of submarines as minelayers.

In the first two years of the war, the British experienced a number of problems with the reliability of their mines, due to the mechanical firing arm used. Later on, they successfully employed the Hertz horn system. The new mines helped to make an effective mine blockade in the English Channel. A notable British development with great future potential was the magnetic influence mine called the M-Sinker.

During 1914-1918, the British laid over 128,000 mines of which around 40 per cent were in enemy waters in the Heligoland Bight, the Kattegat, off the Belgian coast and in the Mediterranean. The United States also laid over 56,000 mines in the Northern Barrage. The British also laid large protective systems in the Dover area, in the Thames estuary and off the Yorkshire coast [Ref. 3].

The Russians laid a considerable number of minefields in the Baltic, the Black Sea and the Gulf of Finland. The French assisted in the Mediterranean. The majority of the

neutral nations in Europe laid small minefields in order to defend their own territorial waters.

As a result of all these activities, approximately 150 German warships and auxiliary ships were sunk, including some U-boats.

The Germans laid over 43,000 mines, most of them in small fields around England, France, Italy and Greece, along the eastern shores of the Adriatic, in the Baltic and Black Seas, etc. These mines inflicted Allied losses of about 586 ships, including warships, auxiliary ships and merchant ships [Ref. 2].

Mines had at last become accepted as having an important and significant role to play in naval war strategy.

C. USES OF MINES DURING AND AFTER WORLD WAR II

Before the breakout of World War II in 1939, the British, with the experience gained from the enemy's tactics during World War I , had been formulating plans on minelaying operation in order to be ready as soon as war was declared. The first minefields to be laid after war was declared were in British waters. The French cooperated by laying further minefields off Dunkirk and in the inshore channels.

World War II German mines were, as a whole, cleverly designed. The Germans boasted that they were going to use a secret weapon which would be impossible to counteract or recover, but the British were able to discover their secret

when one of the magnetic mines was captured. The main British response was the degaussing of ships. This proved to be highly successful; in the early summer of 1940 the number of sinkings through magnetic mines dropped dramatically. But degaussing of ships was not the complete answer, especially in shallow waters. A practical way of sweeping and destroying mines also had to be found. This was the next step in the war against German mines.

A battle of wits was beginning. By the end of 1940 the Germans had introduced 2 new devices into their mines. The first one was a counter device, and the second was an arming delay which prevented the mine from coming alive until after a preset time had elapsed. The effect of these devices was to complicate the sweeping operation by the Allies. At the same time the German acoustic mine was introduced into the war, and still later a combined magnetic-acoustic mine was developed. The last card played by the Germans was the introduction of the pressure mine. Each of these introductions led to corresponding countermeasures on the part of the Allies.

As a result of Allied, and especially British, minelaying operations, about 1,050 Axis warships and merchant ships were sunk and a further 540 damaged. The advent of aircraft as minelayers had rendered traffic in waters under enemy control more vulnerable to minelaying attack than it was in World War I. The Germans, besides their great

ingenuity in the development of all types of mines, made enormous use of aircraft and submarines as minelayers, planting over 120,000 mines in the waters of Northwestern Europe. The Italians also laid many mines in the Mediterranean.

The total number of British and Allied ships sunk by German mines was about 577: 281 warships of all types and 296 merchant ships. The total number of Allied merchant vessels sunk was 521 [Ref. 2].

In the Pacific, the mining operation against the Japanese was concentrated in four distinct areas: the Southwest Pacific area, the India-Burma area, the Chinese area, and the Central Pacific area. The need to eliminate Japanese shipping traffic between the islands and the mainland of Asia with Japan was apparent, and these 4 groups were planted in order to accomplish this objective.

This was really a starvation campaign against Japan. The Allies planted 12,000 mines, of which approximately 4,900 mines were magnetic, 3500 acoustic, 3000 pressure and 700 low frequency-acoustic mines. The Japanese lost 670 ships, including 65 warships. Of these 294 were sunk, 137 damaged beyond repair, and 239 able to be repaired [Ref. 3].

A new family of mines, called "destructors", came into use in 1967 during the Vietnam Conflict. The term "destructor" was employed to circumvent any political

implications resulting from the use of the term "mines" [Ref. 4]. These destructors contained highly sophisticated firing mechanisms which were emplaced in the general purpose bombs.

The modern mine of today has come a long way since the beginning, in terms of sophistication. Not only is the mine more sophisticated and intelligent, but its strategic potential has also steadily increased. It may be unspectacular, but it is one of the most economical and useful weapons ever built for control of the seas.

D. THE MINE IN INTERNATIONAL LAW

The only international agreement on the subject of mine warfare is the "Convention Relative to the Laying of Automatic Submarine Contact Mines", signed at the Hague in 1907.

The following are the main Articles stated in that convention:

> Article I
>
> It is forbidden to lay unanchored automatic contact mines unless they be so constructed as to become harmless one hour at most after those who laid them have lost control over them.
>
> Article II
>
> It is forbidden to lay automatic contact mines off the coasts and ports of the enemy with the sole object of intercepting commercial navigation.
>
> Article III
>
> When anchored automatic contact mines are employed, every possible precaution must be taken for the security of peaceful navigation.
>
> The belligerents undertake to provide, as far as possible, for these mines becoming harmless after a

limited time has elapsed, and where the mines cease to be under observation, to notify the danger zones as soon as military exigencies permit, by a notice to mariners , which must also be communicated to the governments through the diplomatic channel.

Article IV

Neutral powers which lay automatic contact mines off their coasts must observe the same rules and take the same precautions as are imposed on belligerents.

The Neutral Power must give notice to mariners in advance of the places where automatic contact mines will be laid. This notice must be communicated at once to the respective governments through the diplomatic channel.

Article V

At the close of the war, the Contracting Powers undertake to do their utmost to remove the mines they have laid, each Power removing its own mines.

As regards anchored automatic contact mines laid by one of the belligerents off the coast of the other, their position must be notified to the other party by the Power which laid them and each Power must proceed with the least possible delay to remove the mines in its own waters.

Article VI

The Contracting Powers which do not at present own perfected mines of the description contemplated in the present Convention, and which, consequently, could not at present carry out the rules laid down in Articles I and III, undertake to convert the material of their mines as soon as possible, so as to bring it into conformity with the foregoing requirements.

Article VII

The provisions of the present Convention are only applicable between the Contracting Powers, and only if all the belligerents are parties to the Convention.

Article VIII, IX, X, XI, XII, AND XIII

These Articles dealt with the ratification of the Convention, the accession of non-signatory Powers, the date on which it should take effect, the period for which it should remain in force, the reopening of the question of the employment of automatic contact mines, and the keeping of a register at The Hague. [Ref. 2]

This Convention was due to reconvene in 1914, but World War I intervened. Thus the Articles of 1907 remain the sole instrument for the conduct of mine warfare today.

III. CHARACTERISTICS AND TYPES OF MINES AND MINEFIELDS

Today's mines are designed to be deployed against many different types and classes of ships, to achieve a variety of results. However, in order to accomplish their various missions, mines are being designed and constructed with ever increasing complexity. The number of different missions to be performed by mines is so large that no single type of mine can be used for all purposes. Some of them have a small explosive charge designed to be used against vessels of small displacement. Others have a large explosive charge to destroy or damage such capital ships as frigates, cruisers, destroyers and merchant ships. Some mines are constructed primarily to destroy submarines.

The increased complexity of mines is due primarily to the computer intelligence built into their firing systems. The same technology which makes mines more complex in some ways also makes them simpler in other ways. The new mines have features which make their assembly, testing and stowing much safer and easier than was previously the case with older mines [Ref. 5].

A. TYPES OF MINES

Mines can be classified according to three main characteristics: position in the water, objective, and method of actuation. We discuss each type in turn.

1. Position In Water

From the standpoint of the position they assume in the water, mines fall into three categories:

- bottom mines
- moored mines
- drifting mines

as explained below.

a. Bottom Mines

These mines are very effective in shallow waters. They lie on the bottom of the ocean, sometimes buried in the mud, awaiting a passing ship. Bottom mines do not normally move about once planted.

In deep waters, a surface ship can pass over a bottom mine without actuating its firing mechanism, or may not suffer much damage even if the mine activates. Nevertheless, this type of mine can still be effective against submarines when planted in deep waters.

b. Moored Mines

These mines are used for deep waters. They are effective weapons against both submarines and surface ships. The firing mechanism and its explosive charge are housed in a positive buoyancy case.

This type of mine stays at a predetermined depth below the surface, held by a cable which is attached to an anchor on the sea bottom. It is free to move about within the limits permitted by the cable.

c. *Drifting Mines*

This kind of mine floats freely at or near the surface of the water. Its buoyancy is approximately neutral and the mine has a mechanism to keep it at a certain constant depth. The Hague Convention of 1907 limits the use of this mine.

2. Objective Of A Minefield

Depending on the objective of the minefield, the actuation of individual mines can fall into two main categories:

- controlled mines (defensive)
- independent mines (offensive)

as described below.

a. *Controlled Mines*

As their name indicates, these mines are always under human control, sometimes being controlled completely from an observation post ashore (so that the mine may be detonated as desired). Alternatively, shore control may be limited to arming or disarming the firing mechanism, letting the detonation of the mine depend on its own sensors. The greatest defensive benefit of controlled mines is to let friendly ships pass safely through the field. Controlled mines are used primarily for harbour or port defense purposes.

b. Independent Mines

Independent mines are used for all purposes other than the close defense of own one's harbors and ports. Once laid, they normally remain dangerous to any friendly, enemy or neutral ship until they are swept or scuttled. They may also encounter natural deterioration which renders them harmless.

These mines are activated by the presence of a ship, either by physical contact or by one of several influence mechanisms.

3. Method Of Actuation

There are three different commonly used methods of actuation:

- magnetic
- acoustic
- pressure

Moreover, these methods of actuation can be used in combination resulting in a diversified mix. These combinations not only increase the mine's detection capability, but also make countermining more difficult for the enemy.

a. Acoustic Mines

The acoustic mine is equipped with a hydrophone as its detector. The acoustic firing mechanism converts underwater sounds made by propeller and machinery noises from ships into electrical signals for analysis and processing. This firing mechanism responds only to sounds

that are within a given frequency band. The mechanism must be able to recognize underwater sounds that are being produced by invalid targets, such as countermining explosions or marine life sounds. The recognition of a valid acoustical signature detonates the mine.

b. Pressure Mines

These mines react to the phenomenon that a ship in shallow water creates two pressure waves on the bottom of the sea, separated by a low pressure area. The pressure firing mechanism works together with pressure detectors to detect and evaluate the presence and validity of a potential target. If the analysis shows that a given signal meets the specific requirements for a valid target and lies within the mine's damage area, the mine explodes. Otherwise it retains its charge and does not fire.

This is the most difficult type of mine to sweep.

c. Magnetic Mines

This thesis now restricts itself primarily to the study of the magnetic mine.

Today, most ships are made of iron and steel. Even wooden ships have iron parts, such as nails and machinery. These magnetic materials, immersed in the magnetic field of the earth, acquire a net magnetization of their own, made up of two parts: a permanent magnetization

and an induced magnetization. We now discuss these two types of magnetization.

The permanent magnetization of a ship depends on its size and types of materials, as well as on where it was built and the orientation of the keel in the shipyard. This magnetization has horizontal, vertical and athwartship components. These three components of induced magnetization depend upon the ambient magnetic field of the earth. This field depends on the ship's location. A magnetic mine is constructed in such a way that a disturbance of one of the components of the earth's magnetic field activates the mine's firing mechanism. The magnetic firing mechanism involves one of the following two types of target detectors: the search coil or the magnetometer. Both of these types give input to the firing mechanism, but they differ in their method of detection.

Search coils are used to sense changes along one axis of the earth's magnetic field. The presence of a passing ship can cause such a change. The target detector equipped with a search coil is excellent for bottom mines, since these mines, once planted on the sea bed, assume an unchanging position.

On the other hand, the magnetometer has a three dimensional or total field detector. This mechanism is an ideal detector for moored mines which, by their nature, are constantly changing orientation because of an unstable

environment. The firing mechanism works in conjunction with the magnetic detector, evaluating and analyzing if the inputs are coming from a valid target operating within the mine's damage range. If the analysis concludes that the signal meets the requirements of an enemy ship, the mine detonates.

B. TYPES OF MINEFIELDS

1. Objective Of The Minefield

Depending on its objective, a minefield, can be of two types:

- defensive
- offensive.

a. Defensive Minefields

A defensive minefield is planted in waters under a nation's own control. Its purpose is to protect ports from enemy attack, to keep hostile submarines out of harbors and entrances, and to deter an enemy invasion force.

During the Korean war the United States Navy was barred access to the North Korean port of Wonsan due to enemy minefields. The fleet Commander, Rear Admiral Smith, informed the Pentagon that the U.S. Navy had lost command of the sea in Korean waters. Admiral Joy was to say later that,

> no so-called subsidiary branch of the naval service, such as mine warfare, should ever be neglected or relegated to a minor role in the future. [Ref. 1]

It is apparent from this historic example that although the U.S. Navy was a superior open-ocean naval force to the North Koreans, defensive minewarfare was able to, at least temporarily, defeat U.S. Navy objectives in the coastal waters of North Korea.

Mines also may be used near a landing beach in order to protect one's own amphibious forces from attack by submarines or other kinds of vehicles. Defensive minefields are often constructed with the mines under control from a shore station. The minefield is laid out by any type of vehicle, but primarily by surface ships.

b. Offensive Minefields

The principal characteristic of this type of minefield is that the mines are planted in waters under enemy control. The objectives are to attack and destroy enemy shipping, to deny effective use of the enemy's ports, or to establish a blockade by laying mines around shipping lanes.

Offensive minefields are constructed with independent mines. Once planted, they do not distinguish between friend or foe. Secrecy is often very important and it is sometimes the key to a successful operation. The minefield is usually laid by submarines or aircraft.

A recent use of an offensive minefield occurred in the Persian Gulf in the 1980s, where the old fashioned moored contact mine proved to be an effective weapon. Mines do not have to be sophisticated to be effective.

2. Disposition Of Mines

According to how the mines are arranged in the minefield, disposition of the mines can be divided into two groups:

- pattern minefield
- random minefield.

a. *Pattern Minefield*

These are fields where the mines are planted according to a specific pattern. Normally they are laid out in a series of lines perpendicular to the direction of the shipping lanes, with equal spacing between the mines in each line. The field consists of a specific number of lines that are parallel to each other. Each line has the same probability of sinking a ship, assuming that the ship has not been sunk before.

b. *Random Minefields*

In practice, due to time constraints or method of deployment (ie., aircraft), it may not be possible or desirable to plant a pattern minefield, but rather to lay the mines in a random fashion without any predetermined pattern. In order to do this effectively it is necessary to know the distance a ship travels inside the minefield in

order to calculate both the area of the region to be mined and the number of mines to be employed. This type of minefield is often of the offensive type.

C. MINE DEPLOYMENT

Mines can be delivered to their respective stations by submarines, aircraft or almost any type of surface ship, possibly requiring a few modifications.

1. Surface-laid Mines

Surface laying is the most economical method of delivery because a large number of mines can be carried in the delivery vehicle. This type of delivery is used primarily for defensive mining operations, and is typically done by minelayers.

2. Submarine-laid Mines

This method of delivery is sometimes used in offensive mining operations. The mines used for this type of delivery system need a special configuration in order to be launched from torpedo tubes. Tactically, submarines can carry mines to great distances from the home port, but they are limited in the number of mines they can take. This may be considered as a disadvantage. However, when secrecy is paramount, the submarine is the preferred minelaying vehicle and provides an overwhelming tactical advantage.

3. Aircraft-laid Mines

This method of deployment is typically employed in offensive mining operations. The mines are delivered from aircraft in much the same way as a bomb. The mines need to have a special configuration for air drop to avoid damage or premature explosion when the mine touches the water. Aircraft have the capability for replenishing minefields over a long period of time, without being exposed to previously laid mines. Most aircraft that carry bombs can lay mines.

D. MINE COUNTERMEASURES

The countermeasures employed in minewarfare can be classified into three general types:

- Special equipment on ships
- Physical removal
- Circumnavigation.

1. Special Equipment On Ships

In order to prevent the actuation of the firing mechanism of the mines, special equipment must be installed on the ship. Such equipment varies with the type of mine that a ship has to defend itself from.

Against magnetic mines, ships are equipped with degaussing coils to reduce the disturbances produced by the metal parts of the ship on the magnetic field of the earth.

Against acoustic and pressure mines, a limited defense has been achieved in constructing less noisy

machinery. The ship may be also steered more slowly and quietly to produce less noise and water disturbance.

2. Physical Removal

This type of countermeasure employs sweeping operations to be conducted before any ships can pass through the minefield.

Depending on the method of actuation for bottom mines, different types of sweeping activities must be performed in order to destroy them. For magnetic mines, a device that creates a disturbance on the vertical component of the earth's magnetic field can be used to actuate the mines. In the same way, a noise producer may be used to actuate acoustic mines.

The most difficult type of mine to be swept is the pressure mine. The difficulty lies in physically creating a pressure disturbance great enough to explode the mine. For this purpose a device that simulates a large ship is used. However this operation is very expensive.

For moored mines, a cable with a paravane device, to support the cable at its outer end and to hold it out at an angle to the sweeper, is towed through the water. Spaced along the cable are cutting blades which sever the mooring lines of mines encountered. The mines then bob to the surface and can be destroyed. [Ref. 5]

Minesweeping operations are expensive and time consuming. They can only be successful to a partial

degree. One can never be completely sure that all the mines have been totally eliminated.

3. Circumnavigation

For safety reasons, if the exact location of a minefield is known and if shipping can be re-routed without undue inconvenience, this procedure is often recommended.

IV. UNDERWATER EXPLOSIONS

A. UNDERWATER EXPLOSION PRINCIPLES

1. The Initial Shock Wave

When a charge is exploded under water a shock wave, or instantaneous pressure pulse, is emitted in all directions. This shock wave travels with the speed of sound in water at about 5,000 feet per second. Figure 1 depicts this phenomenon.

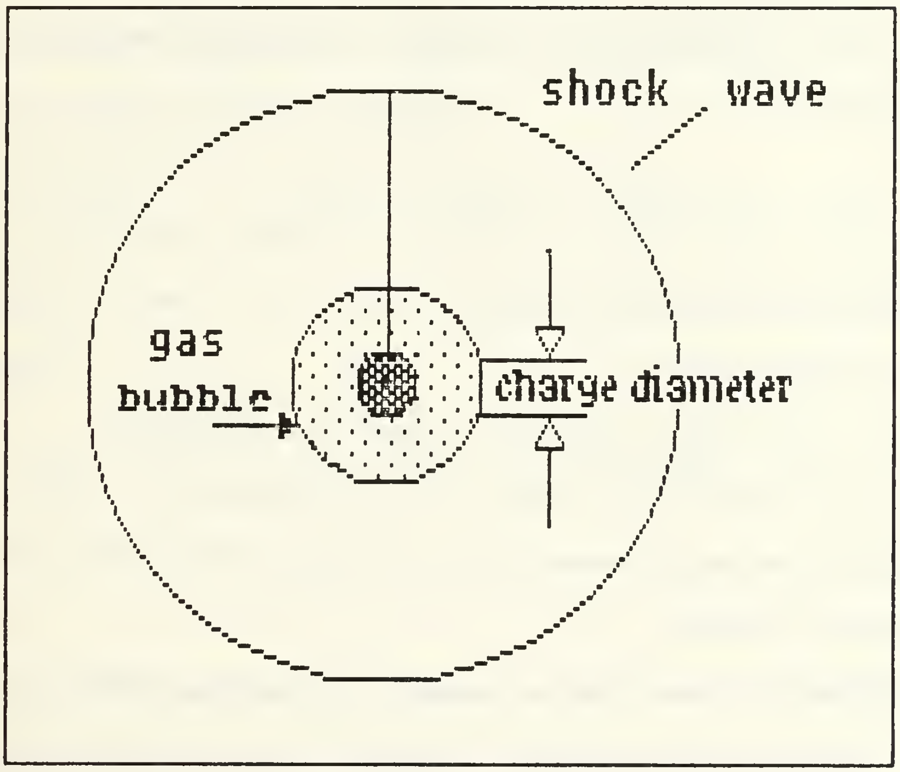

Figure 1 - Diagram Of Shock Wave And Gas Bubble
Of An Underwater Explosion

It has been found that the shock wave, expressed as a relationship between pressure and time, can be approximated by the following function: [Ref. 6]

$$P = P_0 * e^{-t/\theta} \qquad (1)$$

measured in pounds per square inch (psi), where:

P = Shock-wave pressure at distance R

P_0 = Peak overpressure

t = Time after arrival of shock wave

θ = Time constant for the pressure to decay to P_0/e

Both the peak overpressure P_0 and the time constant can be expressed as a function of the charge weight **W** (pounds), and the distance R (feet). The peak overpressure is: [Ref. 6]

$$P_0 = 21{,}600 * (W^{1/3} / R)^{1.13} \qquad (2)$$

in pounds per square inch (psi).

The time constant is:

$$\theta = 0.058 * W^{1/3} (W^{1/3} / R)^{-0.22} \qquad (3)$$

given in milliseconds (msec).

2. Bubble Pulses

Following the shock wave, a series of positive pressure pulses are emitted by the gas of the explosive charge. It has been found that the bubble expands until the <u>hydrostatic head</u> of the surrounding water overcomes the

internal gas pressure. At this point the bubble collapses and the gas is compressed into a small volume. The gas expands again and the expansion and collapse cycle is repeated.

For explosives, the time interval **T** (sec) between the arrival of the first shock wave and the shock wave due to the collapse of the the first bubble is expressed by: [Ref. 7]

$$T = \frac{K \; * \; W^{1/3}}{(D + 33)^{5/6}} \tag{4}$$

where:

K = Proportionality constant, 4.36 for TNT

W = Charge weight in pounds

D = Depth of the detonation in feet

With increasing depth of detonation, the time interval decreases and the pressure amplitude of the bubble increases.

In attack situations where explosions occur near the ship and especially if they occur under the ship, the bubble pulses add significantly to the damage to the ship's hull.

Bubble pulses are not considered in **MINIPLAN** since the amount of energy carried by the shock wave is much greater than the energy left in the bubbles [Ref. 12].

B. THE SHOCK FACTOR

The likelihood of damage to a ship can be determined by the following parameters: charge weight, explosion composition, oceanic conditions, hardness and depth of the ocean floor, position of the charge relative to the ship, and the type of ship. A variable incorporating some of these factors which gives a rough estimate of the damage that might be incurred to the ship is known as the **Shock Factor**.

The shock factor can be expressed as a relationship between charge weight **W**, slant range R from the mine to the hull, and the angle α between the ocean surface and the line from the hull to the explosive (see Figure 2). The shock factor is given by the following function [Ref. 8].

$$\text{SHOCK FACTOR} = S = \frac{\sqrt{W}}{R} \frac{1 + \sin(\alpha)}{2} \qquad (5)$$

where:

W = Charge weight of explosive (TNT) in pounds

R = Slant range to hull in feet

α = Angle between the ocean surface and the line from the explosive to the nearest point of the hull.

Each type or class of vessel is designed and constructed to absorb without damage a specific shock factor. For very small values of shock factor (about 0.001), no damage occurs to the structure of the ship

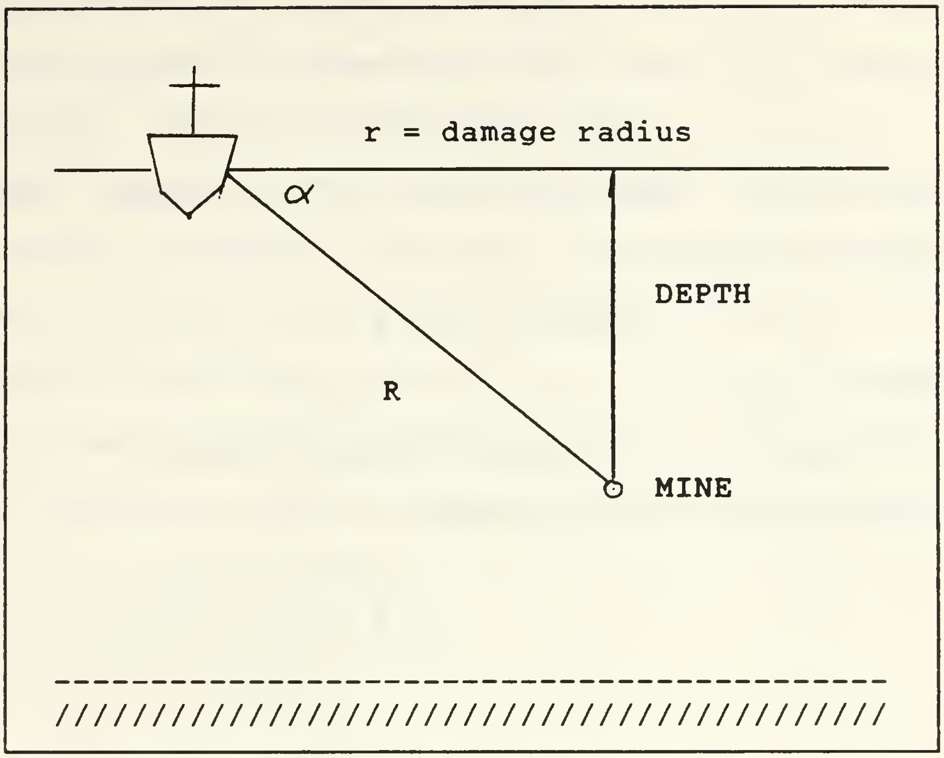

Figure 2 - Graphical Representation Of The Damage Radius

(although the shock will be felt). As the shock factor increases, sensitive electronic equipment is broken, poorly supported or corroded pipes and fittings are broken, and so forth. Finally a higher value of the shock factor is reached and the ship hull ruptures.

Research vessels can normally support a shock factor of about 0.05 without significant hull damage. A factor of 0.01 is usually acceptable for most ships, although some sensitive electronic systems may require a lower value of about 0.003 to withstand damage. Military vessels are designed to considerably higher standards to withstand

greater shock factor values. The shock factor gives a good estimate of a limit for withstanding damage to the hull.

In order to find the damage radius r related to the shock factor, the first step is to replace the **sin α** in equation (6) by D/r:

$$\sin \alpha = D / r$$

where:

D = Depth of the explosive charge in feet.

Then the shock factor becomes

$$S = \frac{(\sqrt{W})\,(1 + \sin(\alpha))}{2R} ,$$

$$2RS = (\sqrt{W})\,(1 + D/R)$$

or after algebraic manipulation,

$$2SR^2 - \sqrt{W}\,R - \sqrt{W}\,D = 0 .$$

From the quadratic formula we find:

$$R = \frac{\sqrt{W} + \sqrt{W + 8\sqrt{W} * D * S}}{4S} \qquad (6)$$

where R is measured in feet.

From the Pythagorean Theorem the damage radius is given by:

$$r = \sqrt{R^2 - D^2} \quad (7)$$

where $R^2 - D^2$ cannot be negative (R>D).

Given the specific shock factor at which hull rupture is just barely achieved, knowing the explosive charge weight, and the depth of the mine, the damage radius r can be determined by equations (6) and (7). If the ship passes inside the damage radius it will be sunk (but see chapter 5). This computation can also be performed for different shock factors corresponding to less severe levels of damage.

V. IMPLEMENTATION AND ANALYSIS OF A MINEWARFARE MODEL

Minefield effectiveness may be judged in many different ways. Threat, **[P(sink the first ship)]** is one widely used measure of effectiveness. One difficulty that may arise in using this measure is that the mines have to be set very sensitive in order to sink the first ship that enters the minefield, consequently the influence areas of the mines are large enough that the first ship that enters the minefield may explode several mines, and the resulting exhaustion of the minefield may let subsequent ships pass clear.

There are various other measures of effectiveness that can be considered to evaluate a minefield:

- The probability of sinking a given number of ships out of a specific number of transitting ships.
- The probability that the "i th" ship will be sunk.
- The average number of penetrators out of a specific number of transitting ships given a stopping value.

All these different measures of effectiveness can help to study the effects of mines.

For purposes of this thesis, the number of transitting ships is ten. So, in order to analyze the effects of the mines, a simulation model written by Prof. Alan Washburn was implemented and modified by the author and several tests were conducted.

A. DESCRIPTION OF THE PROGRAM

For the implementation mentioned above a Fortran program called **MINAPLAN** was adapted for running on the IBM PC or compatible microcomputer in an interactive mode. The program runs for several thousand replications. In each replication it generates normal random numbers to simulate the locations of the ships and their sizes and uniform random numbers for the locations of the mines. The program is included in the appendix.

The output of the program is the probability of sinking a specific number, say i ships out of ten ships, the probability that the i th ship is sunk, and the average number of penetrators out of ten ships given a specific stopping value.

1. Sample Size

An important question that has to be answered when dealing with a simulation program is:

- How many trials or replications are needed (n) ?

Usually, sample size n can be found when one value is to be estimated by using a size requirement on the confidence interval for that value. In our trials, we estimated different values, not all independently. One summarizing measure is the average number of penetrators given a stopping value of 10 ships sunk, u, which is one of the output values. We shall use a desired confidence

interval size for this measure as a basis for determining the sample size n.

A 95 % confidence interval around the mean can be determined from the relationship

$$P(\bar{x} - (1.96\ s)/\sqrt{n} < u < \bar{x} + (1.96\ s)/\sqrt{n}) = 0.95$$

where

$\bar{x}$ = Sample mean of penetrator ships

s = Sample standard deviation of penetrator ships

n = Number of replications

1.96 = Statistic based on assumption that x is normal

TABLE 1 - RESULTS ON 95% CONFIDENCE INTERVAL AROUND THE MEAN

n	$\bar{x}$	s	C.I SIZE
1000	4.44	1.808	0.225
10000	3.969	1.758	0.069

As can be seen in Table 1, the more replications one performs, the smaller the confidence interval. So, the number of replications will depend on how big the user wants the confidence interval to be. Subsequent results in this thesis will be based on n = 10,000. For rough preliminary work, however, n = 1,000 will suffice.

2. Probability Of Actuation

The basic tool in determining if an actuation takes place during a ship/mine interaction is the probability of actuation (PACT).

This is the probability that the mine will detonate given that a ship passes inside the area of influence of the mine. This value (PACT) is set by the user. Setting PACT < 1 is a kind of counter-countermeasure for the protection of the mine against sweeping operations. Of course setting PACT too low will let enemy ships pass by without being damaged.

It is important to mention that if the mine does not actuate for one passing ship, it does not imply that it will not actuate for the next one.

3. Probability Of Damage

Given that the mine explodes, it is necessary to test whether the ship is damaged or not. Although the theoretical explanation in chapter 4 defined a damage radius in which the likelihood of a ship being damaged is either certainty or 0, the probability of damage will in reality be a smoothly decreasing function of range. This is due to a number of factors that complicate the probability of damage as range increases. These factors include oceanic conditions, bottom hardness, and difficulties associated with making a mine go off at the point of closest approach. One way to express this

behavior (the method used in **MINAPLAN**) is through the following exponential function.

$$\text{PRODAM} = e^{-R^2}$$

where R is ratio between the ship-mine distance and the damage radius. This function decreases smoothly as R increases, with the point of steepest slope being at R = 0.707.

4. Ship Size Effect

In building a minefield it is necessary to consider the size (displacement) of the transitting ships, since not all the ships entering the field are of the same size.

The bigger the ship, the bigger the chance that the mine will explode, due to the iron and steel parts of the ship and its magnetic influences.

In **MINAPLAN**, every ship has a size (displacement) chosen from a lognormal distribution. Let D be the displacement (in tons) of a target ship and d be the median displacement (in tons) ship of its class. Then W = Ln(D/d) is a normal random variable with 0 mean. The variance of W depends on the target population, an input to **MINAPLAN**. For simplicity the variance used in subsequent examples in this thesis is assumed to be 1.

5. Mine Influence

Assume that the magnetic moment M of a ship is proportional to the ship's displacement D:

$$M = K \times D$$

in gauss cm^3, where K is the proportionality constant.

Treating the ship as a magnetic dipole, the magnetic field at range r is:

$$M / r^3 = (K * D) / r^3 .$$

The mine will detect the magnetic influence if

$$(K*D)/r^3 \geq s,$$

where s is the sensitivity of the mine (in gauss). Dividing both terms in the last inequality by d/DAM^3 gives:

$$[(K * D)/r^3] / [d/DAM^3] \geq s/[d/DAM^3] \quad \text{or}$$

$$(D/d)/(r /DAM)^3 \geq (s * DAM^3)/(K * d)$$

Taking the natural logarithm of each side results in

$$Ln [(D/d)/(r/DAM)^3] \geq Ln [(s * DAM^3)/(K * d)]$$

Setting - **SEN** equal to the right hand side, this can be written as:

$$Ln (D/d) - 3.0 * Ln (r/DAM) \geq - SEN \qquad (8)$$

If inequality (8) is satisfied, then the mine is influenced by the passing ship. Since **W** = **Ln** **(D/d)** and **R** = **r/DAM**, (8) can be rewritten

$$W - 3.0 * Ln(R) + SEN \geq 0, \qquad (9)$$

the form used in **MINAPLAN**.

The variable SEN could be defined by:

$$SEN = Ln[(K * d)/s * DAM^3] = Ln(B_o/s),$$

where B_o = Magnetic field of a standard ship at a distance equal to the damage radius of the mine. When the sensitivity of the mine is such that a standard ship at damage distance is just barely detectable, then SEN = 0. It is important not to make the mine so sensitive that it can be detonated by a ship passing at a distance so far away that no damage is done. On the other hand, a mine with a sensitivity setting so low that most ships are allowed to pass by is equally undesirable. A principal purpose of **MINAPLAN** is to aid the minefield planner in setting mine sensitivity.

B. STRUCTURE OF THE PROGRAM

1. Definition of the Variables

The variables used in the program are defined as follows:

- NMINE : number of mines planted on the crossing line of width equal to FIELDW, chosen as the entrance sector by the transitting ships.
- WEIGHT : charge weight of explosive (in lbs of TNT).
- DEPTH : depth of the mine (in feet).

- SEN : sensitivity factor of the mine. This is a setting in logarithmic form for the mine's sensitivity to changes in magnetic field.

- NSHIP : number of ships to enter the minefield.

- DAM : damage radius of the mine (in feet), which is a function of the weight, depth and shock factor.

- SIGMA1 : standard deviation of the position of the ship to the center of the path (in feet).

- SIGMA2 : standard deviation of the size of the ship.

- FIELDW : is 6 * SIGMA1 + 2 * DAM (in feet).

- SHOCK : shock factor.

- Y(J) : location of the J-th mine.

- Z : position of the ship with respect to the center of the channel.

- W : is the natural logarithm of the ratio between the size of the ship D in tons and the median size ship d in that class in tons.

- PACT : probability of actuation of the mine.

- PRODAM : probability of damage.

- R : ratio between the ship-mine distance and the damage radius.

- P(I) : probability that I out of NSHIP ships are sunk (I = 0, 1 , 2, ..., NSHIP)

- S(I) : probability that the I-th ship is sunk (I = 1, 2, ..., NSHIP)

- Q(I) : average penetrators out of NSHIP ships if the stopping value is I. (I = 1, 2, ..., NSHIP)
- I : number of ships.

- KREP : number of replications.

2. Algorithm

- Step 1 : Input the information to the program : either setting the values beforehand or

interactively during the execution. Constants are assigned to the following variables:

- NMINE
- NSHIP
- SIGMA2
- WEIGHT
- SIGMA1
- SEN
- DEPTH
- SHOCK
- PACT
- KREP

- Step 2 : Calculates the damage radius of the mine using the formula below:

$$RD = \frac{\sqrt{WEIGHT} + \sqrt{(WEIGHT + 8 * \sqrt{WEIGHT} * DEPTH * SHOCK)}}{4\ SHOCK}$$

$$DAM = \sqrt{RD^2 - D^2}$$

$$0 < DAM <$$

- Step 3 : Determines the field width applying the following expression:

FIELDW = 6 * SIGMA1 + 2 * DAM

- Step 4 : Generates normal random numbers for representing location and size of the ships.

Location = Z = [normal rnd number] * [SIGMA1]

Size = W = [normal rnd number] * [SIGMA2]

- Step 5 : Generates uniform random numbers that correspond to the location of mine (j).

Y(J) = FIELDW * [unif rnd number - 0.5]

- Step 6 : Checks if there still exist any mines in the path of a ship. If not, the program tries another ship.

- **Step 7** : Checks if the mine is influenced by a passing ship, considering:

  - The Size of the ship **W**
  - The ratio R = ABS(Z - Y(J)) / DAM indicates the relative position of the ship with respect to the mine.

  - The sensitivity of the mine **SEN** by:

    IF (W - 3.0 * ALOG(R) + SEN < 0)

  If this expression is true, then the mine does not activate. Return to step 6.

- **Step 8** : A uniform random number is generated and compared with the probability of actuation **PACT** set on the mine. If the mine actuates, the program continues to step 10. Otherwise return to step 6.

- **Step 9** : Checks the damage of the ship. If the ship is not damaged go to step 6. Otherwise record the ship as a casualty and consider the next ship.

- **Step 10** : Computation of P(I), S(I), Q(I) after KREP thousands replications.

- **Step 11** : Output of the different probabilities.

The program has the flexibility of allowing the user to select which variables to fix (setting values in the program before execution), according to the analysis desired.

C. AN EXAMPLE

To illustrate the algorithm described above, consider the following example:

The variables considered fixed are:

- NMINE = 10

- NSHIP = 10
- SIGMA1 = 50 feet
- SHOCK = 0.35
- PACT = 0.85
- SIGMA2 = 1.
- KREP = 10,000

The information to be entered interactively is:

- WEIGHT = charge weight of explosive (TNT) = 300 lbs
- DEPTH = Depth of the mine = 35 feet
- SEN = Sensitivity factor of the mine = 0.5

The results of the program are shown in Table 1. A graphic representation of the probability that the I th ship is sunk, S(I), is also depicted in Figure 3.

Since the ships enter the minefield in a column formation, the first ships have the higher probability of being sunk. This is confirmed by the shape of the curve of S(I), shown in Figure 3.

D. ASSUMPTIONS AND TESTS CONDUCTED

1. Assumptions

In reality there may be many distinct kinds of mines available using different influences or combinations of influences with different sensitivity settings. Also there are several types of possible sweep operations that can be employed. For simplicity, the tests conducted in

TABLE 1 - RESULTS ACHIEVED

I	0	1	2	3	4	5	6	7	8	9	10
P(I)	.007	.041	.122	.223	.261	.198	.107	.034	.007	.001	.000
S(I)		.723	.638	.551	.469	.394	.331	.267	.218	.191	.147
Q(I)		0.54	1.51	2.86	4.27	5.32	5.84	6.03	6.07	6.07	6.07

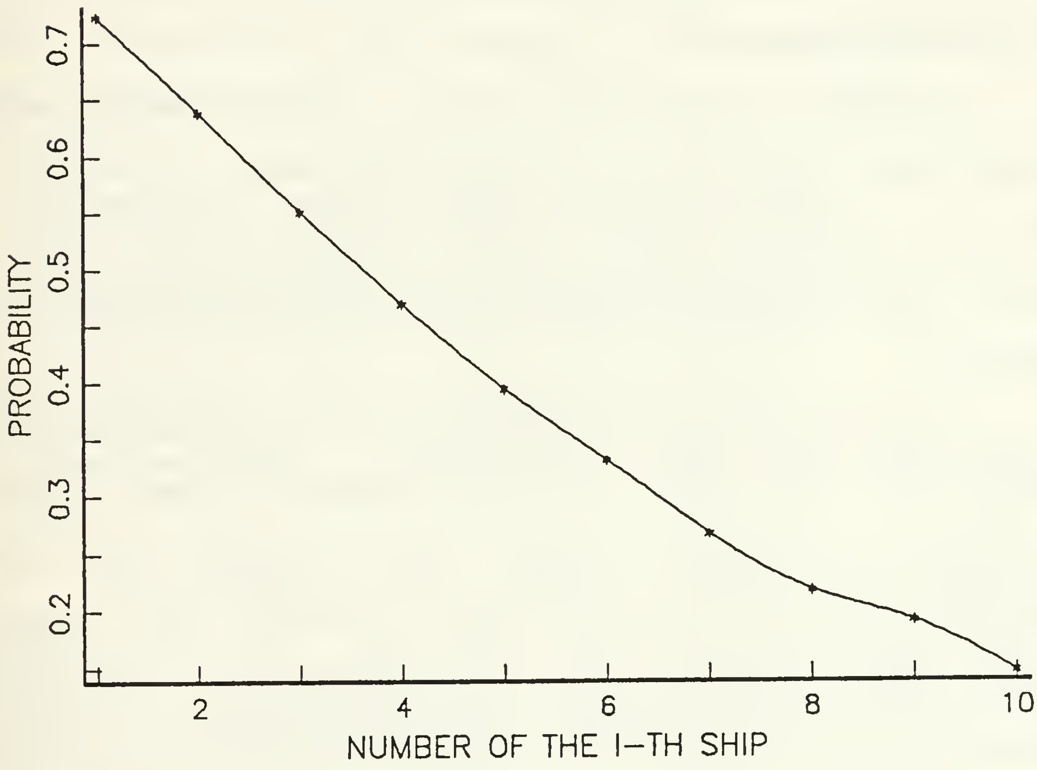

Figure 3 - Probability That The I-th Ship Is Sunk

this study were performed based on the following assumptions:

- The mines are planted at random.
- The type of mine planted is a moored mine.
- The influence type of the mine is magnetic.
- The number of ships to enter the minefield is 10

- The ships enter the minefield in a column formation, having a deviation due to navigation errors from the center of the path chosen.
- The mines are all set with the same charge weight of explosive, depth and sensitivity.
- There are no sweeping or countermeasure operations.
- All ships are of the same type, but with different size.
- After being influenced by a ship, a mine detonates or not depending on its probability of actuation.
- The shock factor chosen for these tests is 0.35.

2. Test Conducted

Consider a nation that has a limited number of a certain type of magnetic mine and that needs to protect a particular entrance against enemy shipping using mines. Assume the minefield characteristics as stated before in Section C.

Considering this scenario, we concentrate our analysis in the study of the effects caused in the probability of sinking i ships out of NSHIP, P(I), the probability that the i-th ship is sunk, S(I), and the average number of penetrators out of NSHIP given a specific stopping value, Q(I). The decision maker is concerned about the effects of the depth, DEPTH, and sensitivity, SEN, settings of the mines.

The intervals of these variables considered here are from 15 to 35 feet (in steps of 5) for the depth and from -1.5 to 1.5 (in steps of 0.5) for the sensitivity.

The results achieved after running the program for all the possible combinations are presented on the Tables 2 through 6.

Depending on the information of interest required by the top command, the tactical situation and the data available, the planner will conduct his analysis and will suggest the settings that will provide the most effective minefield. In order to demonstrate how the analysis could be performed, it was considered that the staff of the navy needs assistance with respect to five main measures of effectiveness:

- Probability that at least 1 ship is sunk.
- Probability that at least 5 ships are sunk.
- Probability that the first ship is sunk.
- Probability that the third ship is sunk.
- Average number of penetrators given the stop value of 3.

For evaluating the effects of depth and sensitivity settings in the situation under consideration and to present a recommendation for achieving better results for each MOE, we use the information contained in Tables 2 to 6. Also, a graphical representation of the information is depicted in Figures 4 through 13. These plots help to confirm visually the settings of depth and sensitivity that will lead to better values for the MOEs.

TABLE 2 - RESULTS OF THE PROGRAM

DEPTH = 15 FEET												
NSHIP		0	1	2	3	4	5	6	7	8	9	10
SEN	P(I)	.007	.047	.141	.247	.265	.186	.084	.020	.003	.000	.000
	S(I)		.590	.532	.472	.421	.383	.335	.295	.260	.238	.204
-1.5	Q(I)		0.86	2.11	3.59	4.95	5.78	6.15	6.25	6.27	6.27	6.27
SEN	P(I)	.005	.039	.123	.230	.265	.203	.098	.032	.004	.000	.000
	S(I)		.643	.574	.510	.451	.397	.346	.300	.252	.232	.191
-1.0	Q(I)		0.70	1.80	3.20	4.56	5.49	5.93	6.07	6.10	6.10	6.10
SEN	P(I)	.005	.035	.117	.215	.257	.215	.114	.037	.006	.001	.000
	S(I)		.691	.613	.543	.473	.406	.347	.298	.247	.219	.175
-0.5	Q(I)		0.59	1.56	2.90	4.26	5.24	5.77	5.95	5.98	5.99	5.99
SEN	P(I)	.005	.032	.109	.210	.261	.212	.120	.043	.009	.001	.000
	S(I)		.733	.652	.566	.487	.409	.346	.285	.234	.205	.157
0.0	Q(I)		0.49	1.38	2.66	4.03	5.11	5.67	5.87	5.92	5.93	5.93
SEN	P(I)	.006	.033	.108	.207	.261	.214	.118	.042	.009	.002	.000
	S(I)		.771	.686	.584	.490	.412	.335	.267	.211	.182	.135
0.5	Q(I)		0.43	1.26	2.50	3.90	5.03	5.64	5.86	5.91	5.92	5.93
SEN	P(I)	.006	.039	.116	.215	.251	.212	.112	.039	.009	.001	.000
	S(I)		.802	.710	.598	.486	.395	.310	.240	.189	.157	.114
1.0	Q(I)		0.38	1.19	2.48	3.92	5.06	5.71	5.94	5.99	6.00	6.00
SEN	P(I)	.008	.049	.141	.221	.248	.194	.099	.033	.007	.001	.000
	S(I)		.826	.723	.602	.473	.367	.273	.206	.158	.119	.094
1.5	Q(I)		0.36	1.22	2.60	4.08	5.24	5.88	6.11	6.15	6.16	6.16

TABLE 3 - RESULTS OF THE PROGRAM

DEPTH = 20 FEET												
NSHIP		0	1	2	3	4	5	6	7	8	9	10
SEN -1.5	P(I)	.007	.047	.139	.248	.263	.188	.084	.021	.003	.000	.000
	S(I)		.592	.534	.473	.421	.383	.336	.294	.260	.238	.203
	Q(I)		0.85	2.10	3.57	4.94	5.77	6.14	6.25	6.26	6.26	6.27
SEN -1.0	P(I)	.005	.039	.124	.227	.266	.204	.099	.032	.004	.000	.000
	S(I)		.645	.575	.511	.452	.396	.346	.301	.253	.233	.191
	Q(I)		0.69	1.78	3.19	4.55	5.48	5.93	5.93	6.07	6.09	6.10
SEN -0.5	P(I)	.005	.035	.116	.215	.256	.215	.116	.037	.007	.001	.000
	S(I)		.693	.615	.545	.473	.407	.348	.297	.247	.220	.174
	Q(I)		0.58	1.55	2.88	4.24	5.23	5.76	5.94	5.98	5.98	5.98
SEN 0.0	P(I)	.005	.032	.109	.209	.261	.212	.121	.042	.009	.001	.000
	S(I)		.735	.653	.567	.488	.411	.346	.284	.234	.206	.156
	Q(I)		0.48	1.37	2.65	4.02	5.09	5.66	5.87	5.91	5.92	5.92
SEN 0.5	P(I)	.006	.033	.109	.206	.261	.214	.120	.042	.009	.002	.000
	S(I)		.773	.688	.586	.491	.413	.336	.267	.211	.182	.134
	Q(I)		0.43	1.25	2.49	3.89	5.02	5.63	5.86	5.91	5.92	5.92
SEN 1.0	P(I)	.006	.040	.115	.215	.250	.212	.114	.039	.009	.001	.000
	S(I)		.803	.712	.600	.488	.396	.310	.239	.188	.158	.114
	Q(I)		0.38	1.18	2.47	3.90	5.04	5.69	5.93	5.98	5.99	5.99
SEN 1.5	P(I)	.008	.048	.141	.219	.250	.191	.101	.033	.007	.001	.000
	S(I)		.828	.724	.605	.473	.368	.274	.205	.157	.119	.093
	Q(I)		0.36	1.20	2.59	4.06	5.23	5.87	6.10	6.14	6.15	6.15

TABLE 4 - RESULTS OF THE PROGRAM

DEPTH = 25 FEET												
NSHIP		0	1	2	3	4	5	6	7	8	9	10
SEN	P(I)	.007	.048	.143	.248	.266	.184	.084	.019	.003	.000	.000
	S(I)		.585	.529	.470	.418	.382	.335	.294	.259	.238	.206
-1.5	Q(I)		0.87	2.14	3.63	4.98	5.80	6.16	6.27	6.28	6.28	6.29
SEN	P(I)	.005	.041	.124	.231	.267	.201	.097	.031	.004	.000	.000
	S(I)		.637	.569	.509	.449	.395	.347	.300	.253	.232	.191
-1.0	Q(I)		0.71	1.82	3.23	4.59	5.51	5.95	6.09	6.11	6.12	6.12
SEN	P(I)	.005	.036	.118	.214	.261	.213	.113	.035	.006	.001	.000
	S(I)		.687	.609	.541	.470	.403	.347	.297	.247	.219	.176
-0.5	Q(I)		0.59	1.58	2.93	4.28	5.27	5.79	5.97	6.00	6.00	6.01
SEN	P(I)	.005	.032	.111	.210	.261	.212	.118	.042	.008	.001	.000
	S(I)		.729	.647	.560	.488	.407	.345	.285	.235	.206	.157
0.0	Q(I)		0.50	1.40	2.69	4.06	5.13	5.69	5.89	5.93	5.94	5.94
SEN	P(I)	.006	.034	.110	.209	.262	.212	.117	.041	.009	.001	.000
	S(I)		.768	.681	.581	.487	.409	.334	.267	.213	.183	.135
0.5	Q(I)		0.43	1.28	2.54	3.94	5.06	5.66	5.88	5.93	5.94	5.95
SEN	P(I)	.006	.040	.117	.217	.250	.212	.111	.038	.008	.001	.000
	S(I)		.799	.708	.592	.485	.394	.309	.241	.189	.158	.115
1.0	Q(I)		0.39	1.21	2.51	3.95	5.08	5.72	5.95	6.00	6.01	6.01
SEN	P(I)	.009	.049	.144	.219	.248	.193	.099	.032	.008	.001	.000
	S(I)		.822	.718	.599	.472	.365	.274	.207	.159	.122	.098
1.5	Q(I)		0.38	1.24	2.64	4.11	5.26	5.89	6.11	6.16	6.17	6.17

TABLE 5 - RESULTS OF THE PROGRAM

DEPTH = 30 FEET												
NSHIP		0	1	2	3	4	5	6	7	8	9	10
SEN -1.5	P(I)	.008	.051	.152	.251	.261	.179	.078	.017	.002	.000	.000
	S(I)		.567	.516	.464	.409	.374	.332	.292	.259	.238	.206
	Q(I)		0.93	2.25	3.76	5.11	5.89	6.24	6.33	6.34	6.34	6.35
SEN -1.0	P(I)	.006	.042	.127	.240	.266	.196	.091	.028	.004	.000	.000
	S(I)		.619	.557	.498	.441	.391	.343	.296	.258	.233	.193
	Q(I)		0.77	1.92	3.34	4.72	5.61	6.02	6.14	6.17	6.17	6.17
SEN -0.5	P(I)	.005	.038	.123	.217	.264	.206	.108	.032	.006	.000	.000
	S(I)		.671	.593	.524	.464	.401	.344	.294	.253	.222	.181
	Q(I)		0.64	1.68	3.06	4.41	5.37	5.86	6.02	6.05	6.05	6.05
SEN 0.0	P(I)	.006	.034	.117	.214	.261	.209	.114	.038	.008	.001	.000
	S(I)		.712	.635	.552	.478	.404	.343	.286	.236	.207	.159
	Q(I)		0.54	1.48	2.80	4.17	5.22	5.75	5.94	5.98	5.98	5.99
SEN 0.5	P(I)	.006	.036	.115	.213	.263	.207	.114	.037	.008	.001	.000
	S(I)		.750	.666	.570	.483	.406	.331	.268	.213	.183	.138
	Q(I)		0.47	1.36	2.65	4.05	5.15	5.73	5.94	5.98	5.99	5.99
SEN 1.0	P(I)	.007	.043	.122	.217	.254	.206	.107	.036	.008	.001	.000
	S(I)		.784	.691	.579	.475	.390	.312	.245	.191	.159	.117
	Q(I)		0.43	1.31	2.62	4.06	5.18	5.79	6.00	6.05	6.06	6.06
SEN 1.5	P(I)	.010	.052	.145	.228	.247	.190	.093	.029	.007	.000	.000
	S(I)		.807	.703	.586	.458	.360	.272	.207	.162	.127	.098
	Q(I)		0.42	1.32	2.75	4.24	5.38	5.97	6.17	6.21	6.22	6.22

TABLE 6 - RESULTS OF THE PROGRAM

DEPTH = 35 FEET												
NSHIP		0	1	2	3	4	5	6	7	8	9	10
SEN	P(I)	.009	.057	.165	.256	.262	.165	.069	.014	.002	.000	.000
	S(I)		.537	.494	.443	.389	.366	.326	.289	.261	.238	.214
-1.5	Q(I)		1.04	2.44	4.02	5.29	6.05	6.36	6.43	6.44	6.44	6.44
SEN	P(I)	.008	.046	.141	.248	.266	.184	.084	.021	.003	.000	.000
	S(I)		.589	.534	.474	.420	.386	.336	.291	.258	.236	.204
-1.0	Q(I)		0.87	2.11	3.59	4.95	5.78	6.15	6.25	6.27	6.27	6.27
SEN	P(I)	.006	.044	.129	.228	.271	.191	.098	.030	.004	.000	.000
	S(I)		.637	.569	.508	.448	.386	.342	.296	.255	.226	.189
-0.5	Q(I)		0.73	1.86	3.27	4.62	5.55	5.98	6.11	6.14	6.15	6.15
SEN	P(I)	.006	.038	.126	.220	.265	.200	.104	.034	.006	.000	.000
	S(I)		.684	.606	.537	.462	.392	.339	.290	.237	.213	.164
0.0	Q(I)		0.62	1.64	3.01	4.38	5.38	5.88	6.04	6.07	6.08	6.08
SEN	P(I)	.007	.041	.122	.223	.261	.198	.107	.034	.007	.001	.000
	S(I)		.723	.638	.551	.469	.394	.331	.267	.218	.191	.147
0.5	Q(I)		0.54	1.51	2.86	4.27	5.32	5.84	6.03	6.06	6.07	6.07
SEN	P(I)	.008	.047	.131	.226	.256	.196	.097	.033	.006	.001	.000
	S(I)		.756	.666	.557	.461	.388	.306	.243	.193	.166	1209
1.0	Q(I)		0.49	1.46	2.82	4.27	5.35	5.91	6.09	6.14	6.14	6.14
SEN	P(I)	.011	.056	.149	.236	.250	.183	.083	.028	.005	.000	.000
	S(I)		.780	.681	.562	.446	.355	.275	.212	.165	.136	.100
1.5	Q(I)		0.48	1.46	2.92	4.43	5.53	6.07	6.25	6.28	6.28	6.29

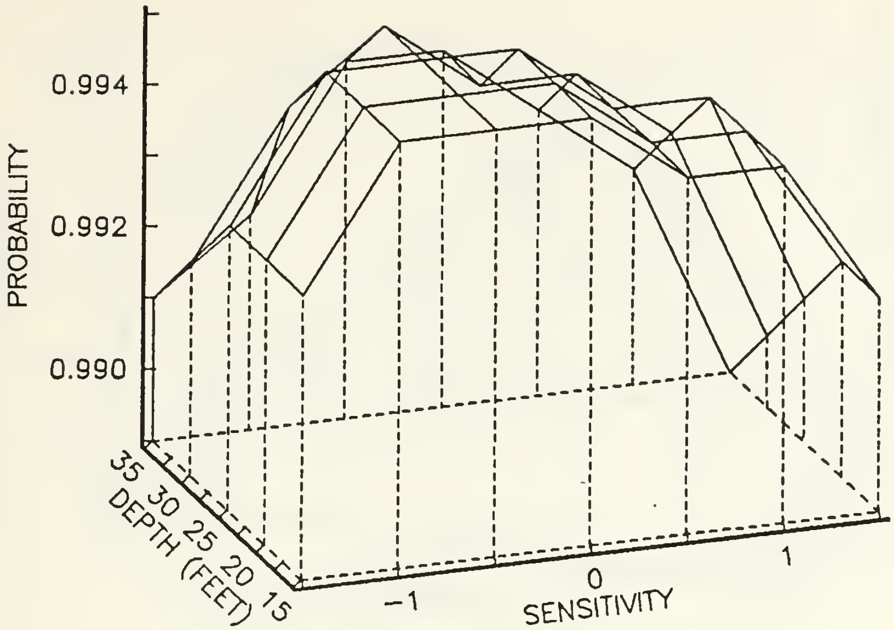

Figure 4 - Tridimensional Plot Indicating P(I ≥ 1)

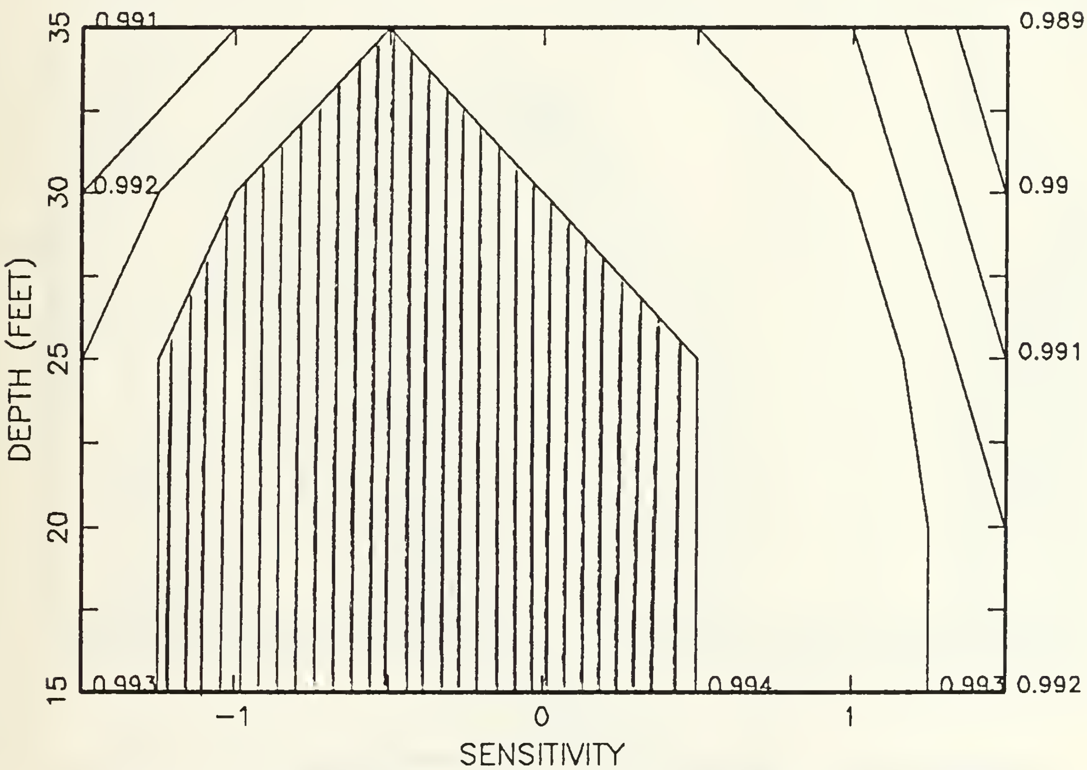

Figure 5 - Contour Plot Indicating P (I ≥ 1)

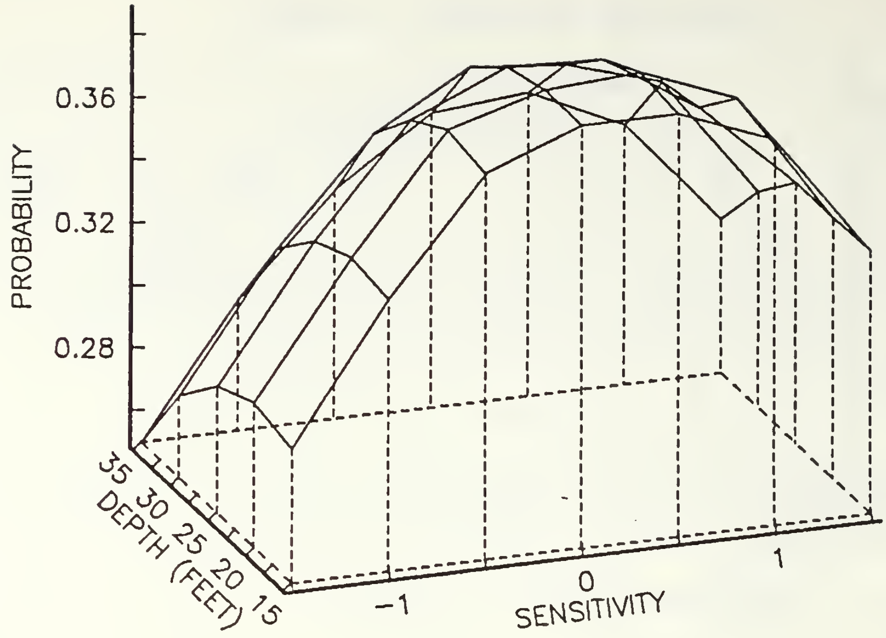

Figure 6 - Tridimensional Plot indicating P(I ≥ 5)

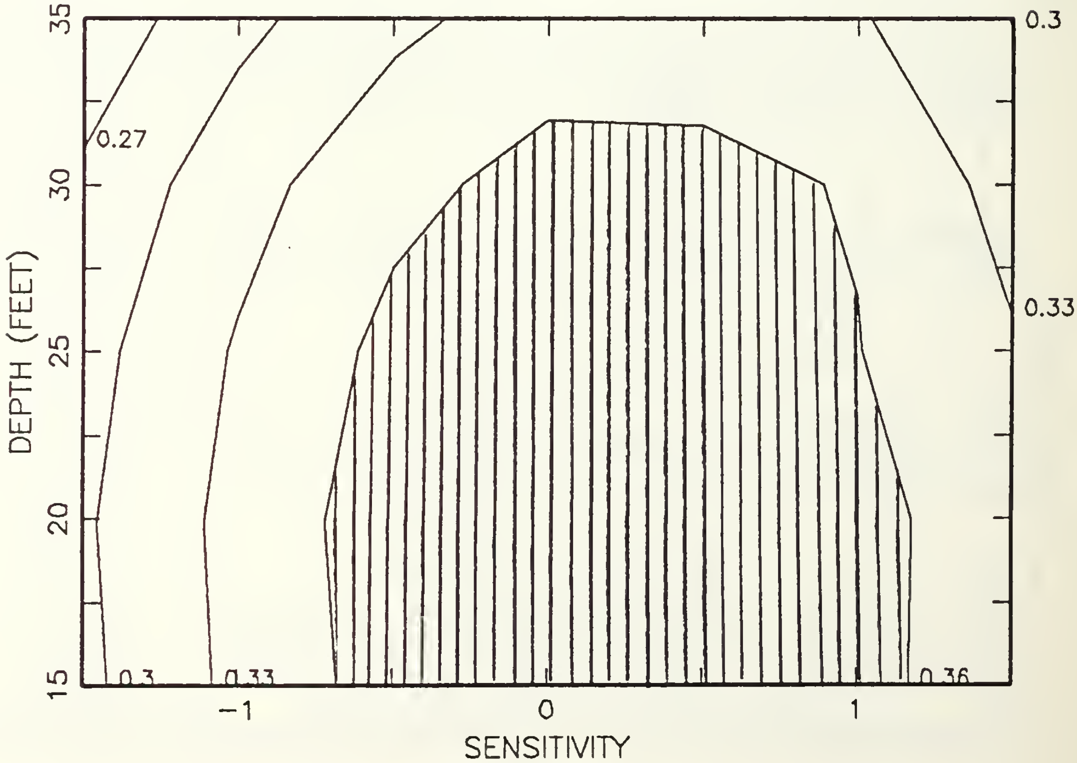

Figure 7 - Contour Plot Indicating P (I ≥ 5)

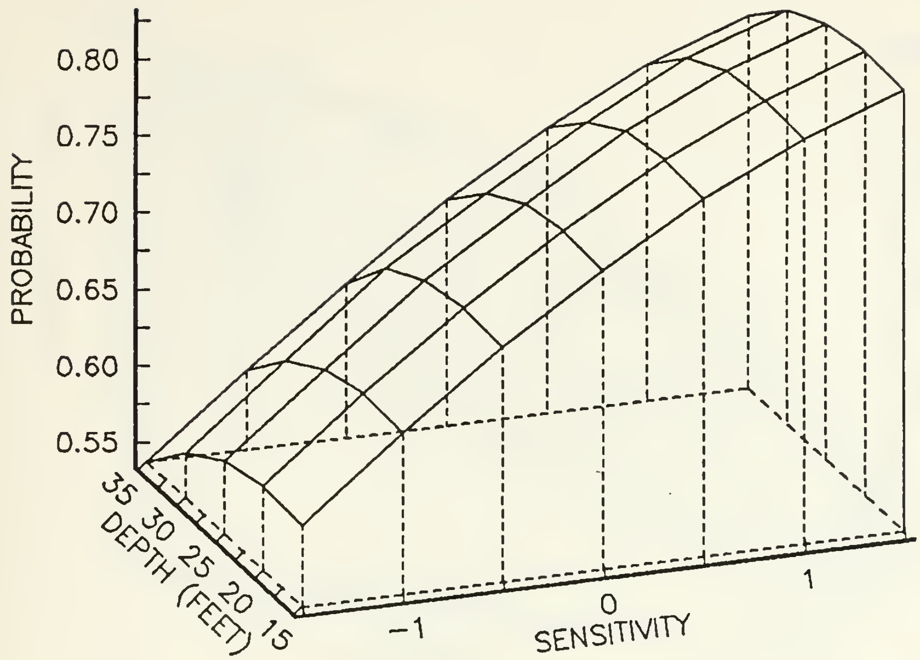

Figure 8 - Tridimensional Plot Indicating The Probability That The First Ship Is Sunk

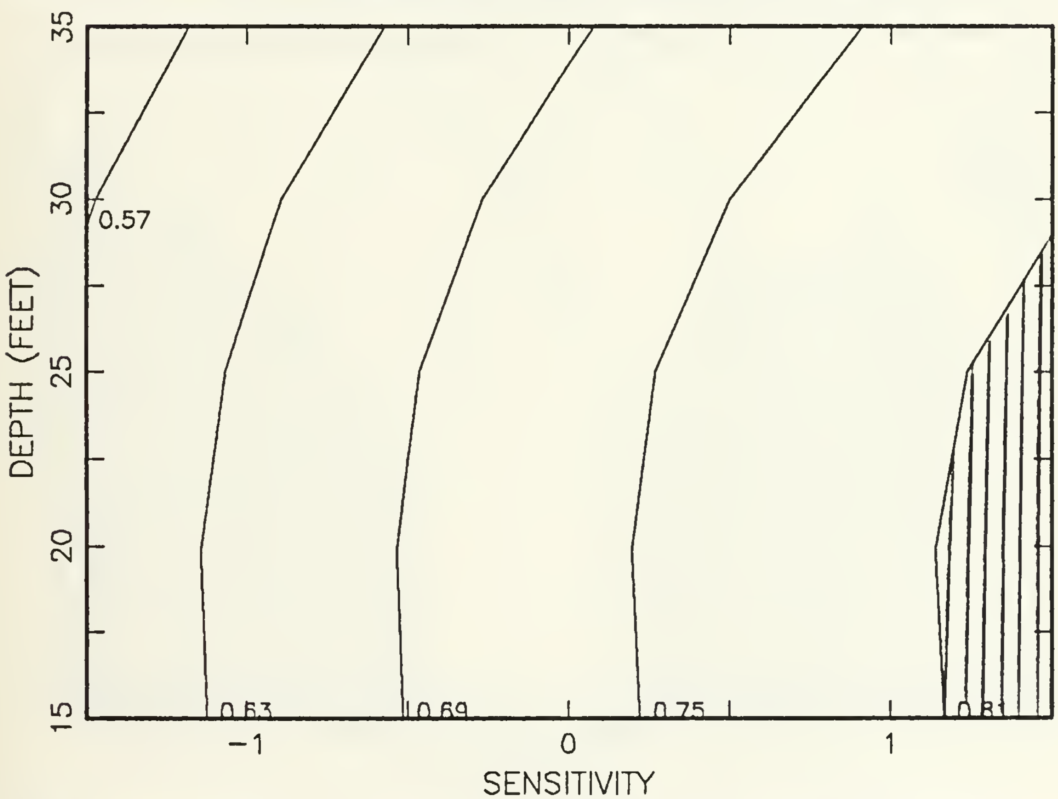

Figure 9 - Contour Plot Indicating The Probability That The First Ship Is Sunk

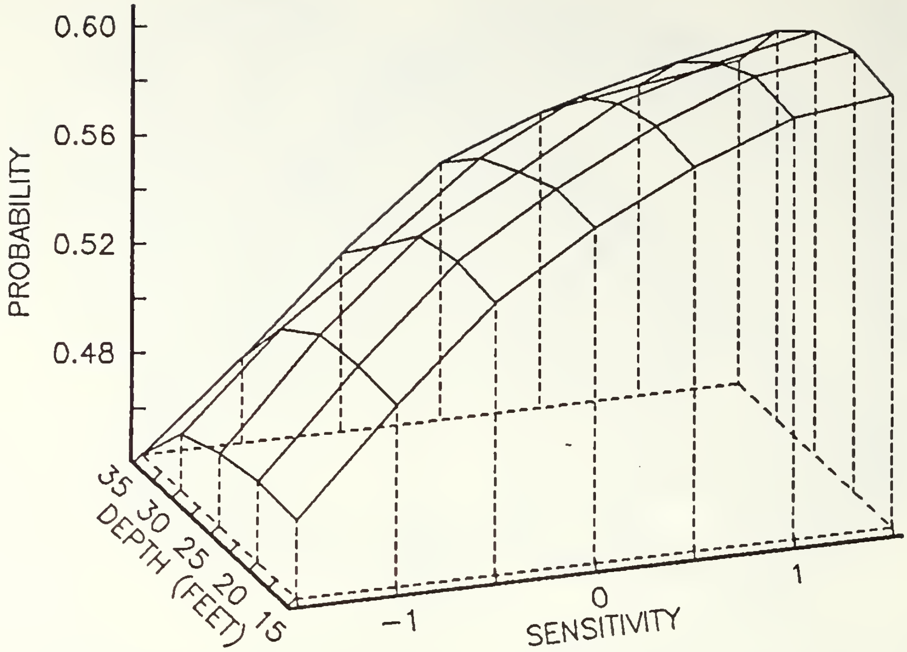

Figure 10 - Tridimensional Plot Indicating The Probability That The Third Ship Is Sunk

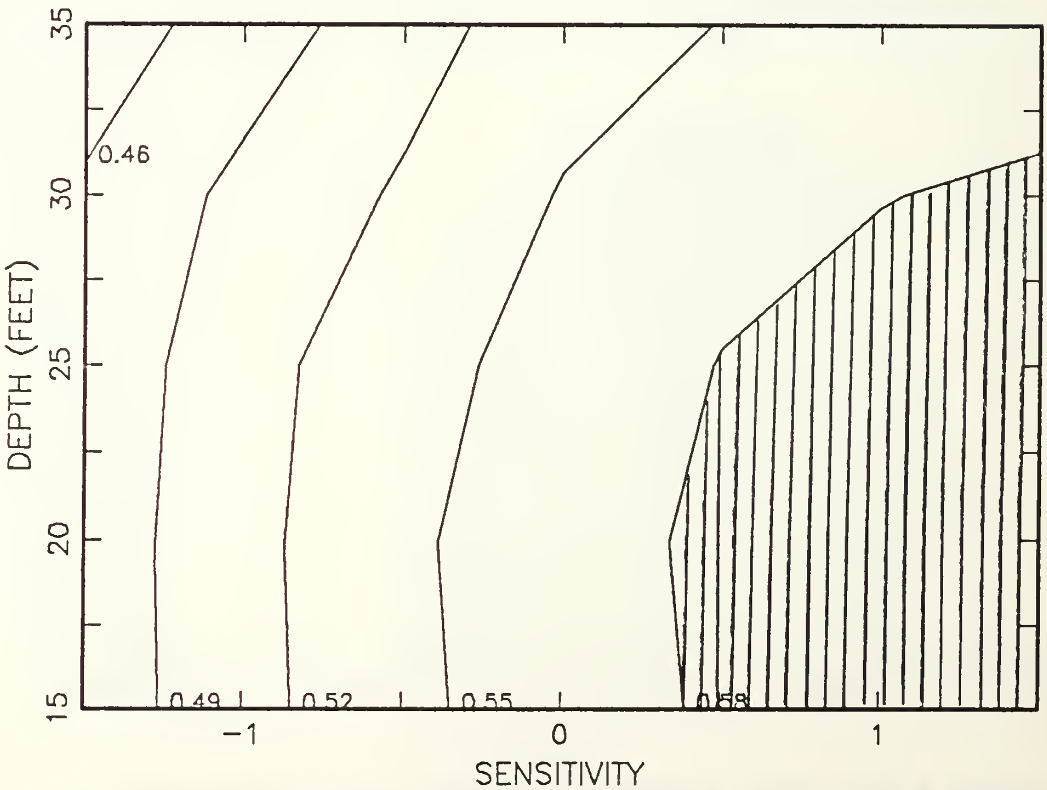

Figure 11 - Contour Plot Indicating The Probability That The Third Ship Is Sunk

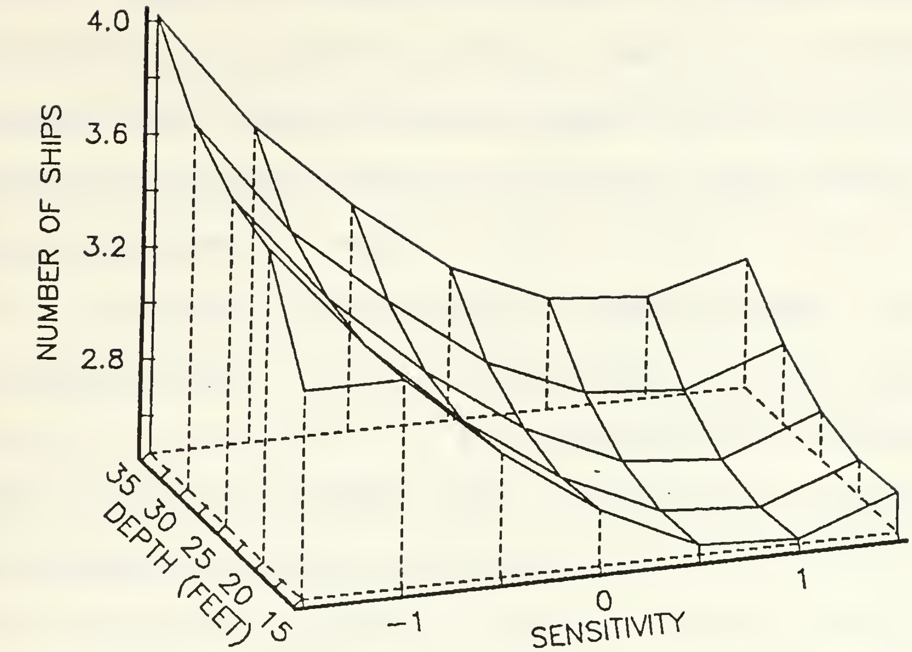

Figure 12 - Tridimensional Plot Of The Average Number Of Penetrators If Stopping Value Is 3

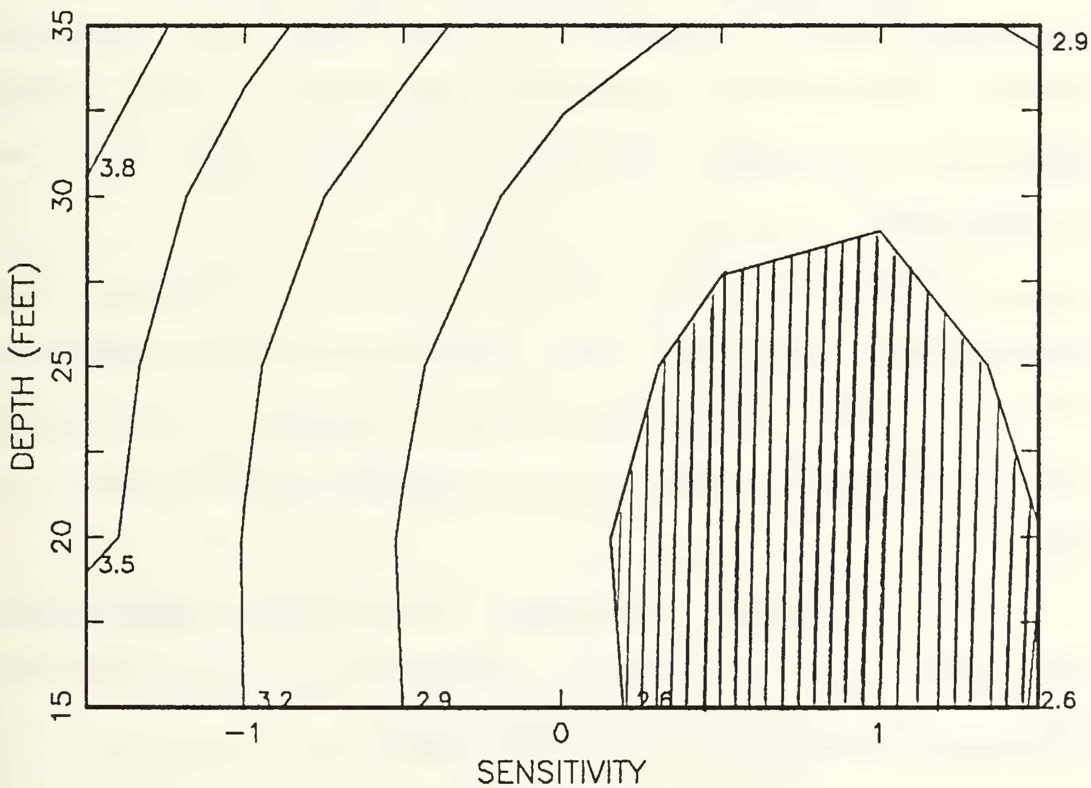

Figure 13 - Contour Plot Of The Average Number Of Penetrators If The Stopping Value Is 3

The settings that correspond to the highest probability that at least 1 ship is sunk are sensitivity equal to -0.5 and depth equal to 15-25 feet. The curves in Figures 4 and 5 above confirm the results obtained from the Tables and also indicate that higher probabilities are achieved for points inside the shadowed areas, i.e., for example, for depth values between 20 to approximately 25 feet and sensitivity between -0.5 to -1.0.

Based on the Tables, the biggest probability that at least 5 ships are sunk is obtained when the sensitivity is set to 0.5 and at 20 feet of depth. The plots also suggest that the probabilities are greater for the points in the shadowed area.

The graphics contained on Figures 4, 5, 6, and 7 confirm that the more ambitious we want to be with the number of sunk ships, the lower the probability of success we will have.

The graphs on Figures 8 and 9 show that the probability that the first ship is sunk increases with positive values of the sensitivity setting. In this case the depth does not have as big influence as the sensitivity does.

As appears in Figure 9, bigger probabilities correspond to a sensitivity setting of 1.5, and for depths between 15 and 28 feet (shadowed area).

Figures 10 and 11 present a visual representation of the probability that the third ship is sunk. As is obvious, the highest probability in this case is smaller than the previous case where the probability was of the first ship.

Points in the shadowed area represent the biggest probability that can be achieved in this situation. For example a probability of sinking of 0.64 can be obtained when setting the mines at sensitivity of 1 and laying them at depths between 15 and 30 feet.

The tridimensional graph of Figure 12 and the contour plot of Figure 13 depict the average number of penetrators for a stopping value of three. This number indicates how many ships,on average, will cross the minefield until three ships are sunk.

In this case the smallest number is the best solution, therefore for example setting the sensitivity to 1 and the depth to 20 feet would give us an average number of penetrators of approximately 2 ships. Again the shadowed area represents the best solution.

Tests and analyses like the ones conducted in this chapter can be carried on, once the top command defines the MOE to be considered when constructing a minefield.

Sometimes the MOE of interest is a multiple MOE. In this situation the intersection of the individuals MOE's shadowed areas will represent the best solution.

E. ANALYSIS OF THE RUNNING TIME

A way to measure the performance of a simulation program is by the running time. The more efficient a program is designed the less time it consumes during execution.

Micro-processor clock speed has an obvious effect on the solution time.

The following is an analysis of **MINAPLAN** running time for an IBM PC/XT with the 8087/80287 math coprocessor, using Ryan-McFarland Fortran, Version 2.10.

The running time of the program depends in large part in how the uniform and normal random numbers are generated by the computer, so an analysis of these procedures is developed below.

1. Uniform Random Numbers

For the generation of uniform random numbers, a Fortran implementation of generator 1 was used [Ref. 9]. This generator is widely used, and its performance thoroughly tested. It is considered to be a good uniform random number generator.

2. Normal Random Numbers

Much of the running time in the program is due to the generation of normal random numbers. Consequently, three different methods for generating these numbers are explored [Ref. 10].

a. Exact Techniques

Two methods using an exact technique for generating standard normal random numbers were examined:

(1) Method 1. Using both equations of Box and Muller [Ref. 10]:

$$Z = (-2 * \mathrm{Ln}(U_1)) * \mathrm{COS}(2*\pi*U_2)$$

$$Z = (-2 * \mathrm{Ln}(U_1)) * \mathrm{SIN}(2*\pi*U_2)$$

The simulation program requires 20 normal random numbers per replication allowing 10 of them for location of the ships and the other 10 for size of the ships. With these 2 equations it is necessary to have a loop repeated 10 times to obtain 20 uniform random numbers.

(2) Method 2. Using a single equation of Box and Muller [Ref. 10]:

$$Z = (-2 * \mathrm{Ln}(U_1)) * \mathrm{COS}(2*\pi*U_2)$$

In order to generate the 20 normal random numbers needed per replication, a loop repeated 20 times must be constructed generating 40 uniform random numbers.

b. Approximation Technique

(1) Method 3. This method uses an approximation to normality, expressed by the following equation:

$$Z = \sum Ui - 6$$

This method uses 12 uniform random numbers to generate 1 normal random number. Thus, to generate the 20 normal random numbers needed per replication it is required to generate 240 uniform random numbers.

Table 7 shows the various running times obtained by using the above methods for 10,000 replications.

TABLE 7 - RESULTS OF THE RUNNING TIME

Method Used		Running Time
1	$Z = (-2 * Ln(U_1)) * COS(2 * \pi * U_2)$ $Z = (-2 * Ln(U_1)) * SIN(2 * \pi * U_2)$	9 min 15 sec
2	$Z = (-2 * Ln(U_1)) * COS(2 * \pi * U_2)$	10 min 25 sec
3	$Z = \sum Ui - 6$	19 min 40 sec

As seen in Table 7, the most efficient method of the three is the Box-Muller (method 1). This method is also easy to program and does not require calculation of the inverse function or excessive computer memory. This method requires one twelfth of the random numbers required by the approximate technique. Trigonometric functions and logarithm calculations are relatively inefficient in a computer, but these inefficiencies are outweighed by the large number of uniform random numbers needed by the approximation technique.

VI. SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDIES

This thesis presents a study about one of the most important subjects in today's Naval Warfare: Mine Warfare. It starts by describing the history of mine warfare, its development and uses through time. Then it states general characteristics and types of mines. It also presents some important concepts on under water explosions. A Fortran program that simulates the passage of a given number of ships through the minefield is described and implemented. The usage of the program with a follow-on analysis of its results either for the evaluation of the effectiveness of a specific minefield or as a part of the decision process in how to better set the mines is demonstrated.

Areas for further research are:

- Consider the use of different types of mines.
- Consider the employment of sweeping operations by the enemy forces.
- Consider the use of counter-counter measures such as:
  - Time delay setting on the mines.
  - Ship counter setting.
- Consider the use of mines with different charge weights of explosive in the same minefield.
- Considered the use of mines with different sensitivity setting in the same minefield.

APPENDIX

FORTRAN PROGRAM

```
*******************************************************************
*                                                                 *
*                                                                 *
*                  ==========================                     *
*                  =   PROGRAM MINAPLAN     =                     *
*                  ==========================                     *
*                                                                 *
*                                                                 *
* Date :    23 / March / 1989                                     *
*                                                                 *
*                                                                 *
*                                                                 *
* Variable definition :                                           *
*                                                                 *
*                                                                 *
*  NMINE   : number of mines planted on the crossing line of      *
*            width equal to FIELDW, chosen as the entrance        *
*            sector by the transitting ships.                     *
*  WEIGHT  : charge weight of explosive (in lbs TNT).             *
*  DEPTH   : depth of the mine (in feet).                         *
*  SEN     : sensitivity factor of the mine. This is a setting *
*            in logarithmic form for the mine's sensitivity to *
```

```
*              changes in magnetic field.                           *
*  NSHIP     : number of ships to enter the minefield.              *
*  DAM       : damage radius of the mine (in feet), which is a      *
*              function of the weight, depth and shock factor.      *
*  SIGMA1    : standard deviation of the position of the ship to    *
*              the center of the path (in feet).                    *
*  SIGMA2    : standard deviation of the size of the ship           *
*  FIELDW    : is 6 * SIGMA1 + 2 * DAM    (in feet).                *
*  SHOCK     : shock factor.                                        *
*  Y(J)      : location of the j-th mine.                           *
*  Z         : position of the ship with respect to the center      *
*              of the channel.                                      *
*  W         : is the natural logarithm of the ratio between the    *
*              size of the ship D in tons and the median size       *

*              ship d in that class in tons.                        *
*  PACT      : probability of actuation of the mine.                *
*  PRODAM    : probability of damage.                               *
*  R         : ratio between the ship-mine distance and the da-     *
*              mage radius.                                         *
*  P(I)      : probability that I out of NSHIP are sunk.            *
*  S(I)      : probability that the I-th ship is sunk.              *
*  Q(I)      : average number of penetrators out of NSHIP if the    *
*              stopping value is I. ( I = 1, 2, ... NSHIP ).        *
*  KREP      : number of replications.                              *
*  I         : number of ship.                                      *
```

```
*  DSEED    : seed for the random number.                           *
*                                                                   *
* Subroutines  :                                                    *
*                                                                   *
*  LRNDPC   : subroutine to generate uniform random numbers.        *
*  LNORMPC  : subroutine to generate normal random numbers.         *
*                                                                   *
*********************************************************************

********  DECLARATION OF THE VARIABLES  ********
      PARAMETER (NUM = 50)
      REAL P(NUM), S(NUM), Q(NUM), Y(NUM), U(NUM), X(NUM), WEIGHT
      REAL SHOCK, DEPTH, R, Z, DAM, FIELDW, CONV, SEN, SIGMA1
      REAL SIGMA2, PRODAM, PACT
      INTEGER NSHIP, NMINE, KREP, NNUM
      DOUBLE PRECISION DSEED
      CHARACTER*1 ANSWER1, ANSWER2
      DATA P, S, Q / NUM * 0., NUM * 0., NUM * 0. /
      DATA X, Y, U / NUM * 0., NUM * 0., NUM * 0. /


******** INITIALIZATION OF THE VARIABLES  ********

C----- Number of ships (NSHIP), std navigation error (SIGMA1)
C----- standard deviation of ships' size (SIGMA2)
```

```
200  NSHIP  = 10
     SIGMA1 = 50.
     SIGMA2 = 1

C----- Number of mines (NMINE), the prob of actuation (PACT)
C----- and the shock factor (SHOCK)

     NMINE = 10
     PACT  = .85
     SHOCK = .35

300   PRINT*, ' INTRODUCE THE NUMBER OF REPLICATIONS IN UNITS OF
   CTHOUSANDS ( 1, 10 ) : '
     READ*, KREP

     CONV = .001/FLOAT(KREP)
     NNUM = 0
     NN   = 0
     NC   = 0
     DSEED = 41

********  INFORMATION INPUT  *********
400  PRINT*, 'ENTER THE CHARGE WEIGHT (lbs), DEPTH OF  THE MINE
            (ft) :'
     READ*, WEIGHT, DEPTH
     PRINT*, 'ENTER THE MINE SENSITIVITY  :'
```

```
      READ*, SEN

******** CALCULUS OF THE DAMAGE RADIUS OF THE MINE ********
      RD =  (SQRT(WEIGHT) + SQRT(WEIGHT + (8 * SQRT(WEIGHT) *
       DEPTH * SHOCK)))
      RD = RD / (4 * SHOCK)
      RR = RD * RD - DEPTH * DEPTH
      ZERO = 0.0
      IF( RR .LE. ZERO ) THEN
         PRINT*, ' THE MINE IS TOO  DEEP TO  CAUSE ANY  DAMAGE ON
THE        CSHIP, TRY ANOTHER VALUE '
         GO TO 400
      END IF
      DAM = SQRT(RR)

****** CALCULUS OF THE FIELD WIDTH OF THE SHIPPING PATH ******
      FIELDW = 6 * SIGMA1 + 2 * DAM


****** TO HOLD PROB(I SUNK), PROB(ITH SUNK), AND AVERAGE ******
****** NUMBER OF PENETRATORS AT STOP LEVEL I              ******
      DO 50 K = 1, KREP
            DO 45 KK = 1, 1000
                  NK = 1
                  NN = NSHIP
```

```
****** GENERATION OF NORMAL RANDOM NUMBERS ******
                 CALL LNORMPC(DSEED,X,NN)
                 NMINE = MINE
                 IF( NC  .LT. NUM-NMINE*(NSHIP+2) ) GO TO 5
                  NC = 0
                 NNUM = NUM


****** GENERATION OF UNIFORM RANDOM NUMBERS ******
                 CALL LRNDPC(DSEED,U,NNUM)


****** ASSIGMENT OF LOCATION TO EACH MINE ******
5                DO 10 J = 1, NMINE
                       NC = NC + 2
                       Y(J) = FIELDW * ( U(NC) - 0.5 )
10               CONTINUE


****** PASSAGE OF THE SHIPS THROUGH THE MINEFIELD ******
                 DO 30 I = 1, NSHIP

******  POSITION OF THE SHIP  ******
                      Z = X(I) * SIGMA1
```

```
******  SIZE OF THE SHIP  ******
                      W = X(I+NSHIP) * SIGMA2
                      J = 0
12                    J = J + 1
13                    IF(J .GT. NMINE) GO TO 30


*****  CHECKING IF A SHIP IS INSIDE THE DAMAGE RADIUS  *****
                      R = ABS(Z - Y(J) / DAM
                      IF (R.LE.0.0001) THEN
                             PRODAM = 1.0
                             GO TO 1
                      ELSE
                         IF(R.GE.5.0) THEN
                               PRODAM = 0.0
                               GO TO 12
                         ELSE
                               PRODAM = EXP(-0.5 * R * R)
                         END IF
                      END IF


*****  VERIFYING IF THE J-TH MINE IS INFLUENCED BY A SHIP  *****
                      IF(W - 3.0 * LOG(R) + SEN .LT. O)GO TO 12
```

```
*****  CHECKING THE PROBABILITY OF ACTUATION OF THE MINE  *****
                        NC = NC + 1
                        IF( U(NC) .GT. PACT) GO TO 12


*****  RE-INDEX THE REMAINING MINES  *****
                        NMINE = NMINE - 1
                        IF(J .GT. NMINE) GO TO 18
                        DO 15 L = J, NMINE
                              Y(L) = Y(L+1)
15                      CONTINUE
18                      NC = NC + 1


*****  CHECKING IF THE SHIP IS DAMAGE  *****
                        IF( U(NC) .GT. PRODAM ) GO TO 13
                        P(I) = P(I) + 1
                        S(NK) = S(NK) + I - NK
                        NK = NK + 1
30                 CONTINUE

35                 Q(NK) = Q(NK) + 1
                   IF(NK .GT. NSHIP) GO TO 45
                   DO 40 I = NK, NSHIP
                         S(I) = S(I) + NSHIP + 1 - NK
40                 CONTINUE
```

```
45          CONTINUE
50    CONTINUE

      DO 60 I = 1, NSHIP
            P(I) = P(I) * CONV
            S(I) = S(I) * CONV
            Q(I) = Q(I) * CONV
60    CONTINUE
      NK = NSHIP + 1
      Q(NK) = Q(NK) * CONV


*******  PRINTING THE OUTPUT OF THE PROGRAM  *******
      WRITE(6,65)NSHIP, NSHIP
65     FORMAT(' PROBABILITY THAT I OUT OF ', I3, 'SHIPS ARE SUNK
     C(I= 0,....,I3, ):'/)

      WRITE(6,70) KREP
70    FORMAT(/ ' PROBABILITY THAT THE I-TH SHIP IS SUNK  (',I2,'
      CTHOUSAND REPLICATIONS):'/)

      WRITE(6,80)(P(I), I = 1, NSHIP)
      WRITE(6,80)(S(I), I = 1, NSHIP)
      WRITE(6,80)(Q(I), I = 1, NSHIP)
80    FORMAT(11F7.3)
      WRITE(6,90) NSHIP
```

```
90    FORMAT(// ' AVERAGE PENETRATORS OUT OF', I4, ' IF STOPPING
     CVALUE IS I : '/ )


******* RUNNING AGAIN THE PROGRAM *******
     WRITE(6,110)
110  FORMAT(// 'DO YOU WANT TO RUN  AGAIN THE  PROGRAM (Y  OR N)
:')
     READ '(A)', ANSWER1

     IF (ANSWER1 .EQ. 'N') GO TO 100
     IF (ANSWER1 .EQ. 'n') GO TO 100

     WRITE(6,120)
120  FORMAT(// 'DO YOU WANT TO CHANGE THE NUMBER OF SHIPS (NSHIP
    C),MINES (MINE), NAVEGATION ERROR (SIGMA1), PROB OF ACTUATIO
    CN  (PACT),  SHOCK  FACTOR  (SHOCK),  STANDARD  DEVIATION OF
SHIPS'      CSIZE (SIGMA2) : ')
     READ '(A)', ANSWER2

     IF (ANSWER2 .EQ. 'N') GO TO 200
     IF (ANSWER2 .EQ. 'n') GO TO 200

     WRITE (6,130)
130   FORMAT(//'INTRODUCE THE VALUES FOR NSHIP, NMINE, SIGMA1,
 CPACT, SHOCK, SIGMA2 : ' )
```

```
      READ*, NSHIP, MINE, SIGMA1, PACT, SHOCK, SIGMA2
      GO TO 300

100   STOP
      END



      SUBROUTINE LRNDPC(DSEED,U,NNUM)
*-------------------------------------------------------------*
*  SUBROUTINE TO GENERATE NORMAL RANDOM NUMBERS               *
*-------------------------------------------------------------*
      PARAMETER (NUM = 50)
      REAL U(NUM)
      DOUBLE PRECISION D31M1, DSEED
      DATA D31M1 / 2147483647.D0 /
      DO 5 I = 1, NNUM
           DSEED = DMOD( 16807.D0 * DSEED, D31M1)
           U(I) = DSEED / D31M1
5     CONTINUE
      RETURN
      END
```

```
      SUBROUTINE LNORMPC(DSEED,X,NN)
*-------------------------------------------------------------*
* SUBROUTINE TO GENERATE NORMAL RANDOM NUMBERS                *
*-------------------------------------------------------------*
      DOUBLE PRECISION DSEED
      PARAMETER (NUM = 50)
      REAL X(NUM), U(NUM),PI
      NNUM = NN + 1
      CALL LRNDPC(DSEED,U,NNUM)
      DO 5 I = 1, NN
           X(I) = (-2 * ALOG(U(I)) )**.5 * COS(2 * PI * U(I+1))
           X(I+10) = (-2  *  ALOG(U(I))  )**.5  *  SIN(2  *  PI *
U(I+1))  5    CONTINUE
      RETURN
      END
```

LIST OF REFERENCES

1. Hartmann, G. K., "Weapons that Wait", Naval Institute Press, 1979.

2. Cowie, J. S., "Mines, MInelayers and Minelaying", Oxford University Press, 1951.

3. Duncan, R. C., "America's use of Mines", United States Naval Ordnance Laboratory, January 1962.

4. "Navsea Mine Familiarizer", Naval Mine Engineering Facility, Rev 2, March 1980.

5. "Naval Operations Analysis", Naval Institute Press, Second edition, 1977.

6. Hollier, R. S., "Direct Shock-Wave Damage to Merchant Ships From Noncontact Underwater Explosions", Paper presented at the April 1959 meeting of the Hampton Roads Section of The Society of Naval Architects and Marine Engineers.

7. Urick, R. J., Principles of Underwater Sound, Mcgraw-Hill Book Company, 1967.

8. "Technical Manual. Explosives Safety Precautions For Research Vessels", Navord Op 3696, March 1966.

9. Lewis, P. A., Orav, E. J., "Simulation Methodology for Statisticians, Operations Analysts, and Engineers", Wadsworth & Brooks/Cole Statistics/Probability Series, 1989.

10. Banks, J., Carson II, J. S., "Discrete-Event System Simulation", Prentice-Hall International Series in Industrial and Systems Engineering, 1984.

11. Low, A. M., "Mine and Countermine", Sheridan House, 1940.

12. Friedman, B., "Theory of Underwater Explosion Bubbles", UnderWater Explosion Research, The Gas Globe, Vol. 2, 1950.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center Cameron Station Alexandria, Virginia 22304-6145	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93943-5002	2
3.	Professor Alan Washburn, Code 55Ws Department of Operations research Naval Postgraduate School Monterey, California	1
4.	Professor Maurice Weir, Code 53Wc Department of Mathematics Naval Postgraduate School Monterey, California 93943	1
5.	Naval Surface Warfare Center, Code U01 10901 New Hampshire Ave Silver Spring, Maryland 20903-5000	2
6.	Lt. Cdr. Newton Rodriguez Lima Brazilian Naval Commision 4706 Wisconsin Avenue, N. W. Washington, D. C. 20016	1
7.	Cdr. Jorge Cruz Game Naval Postgraduate School SMC 2820 Monterey, California 93943	1
8.	Cdr. Jorge Game Caamano Naval Postgraduate School SMC 2820 Monterey, California 93943	1
9.	Lt. Diego Rueda Unit 8 Coastal Route 1 Monterey, California 93940	1
10.	Lt. Oswaldo Rosero Unit 8 Coastal Route 1 Monterey, California 93940	1

11. Office of the Naval Attache 4
Direccion de Educacion
2535 15th. st. N. W.
Washington D. C. 20009

12. Lt. Carlos Vallejo Game 2
Naval Postgraduate School
SMC 2820
Monterey, California 93943